



**APPLICATION OF THE NATIONAL
URANIUM TAILINGS PROGRAM
PROBABILISTIC SYSTEM MODEL
(UTAP) TO THE RABBIT LAKE
URANIUM TAILINGS SITE**

(DSS Reference No. 15SQ.23317-6-1729)

Final Report for:

**The National Uranium Tailings Program
Energy, Mines and Resources Canada**

Prepared by:

**BEAK Consultants Limited
6870 Goreway Drive
Mississauga, Ontario
L4V 1P1**

In Association With:

**Concord Scientific Corporation
and the
Whiteshell Nuclear Research Establishment**

February 1987

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MICROMEDIA

ABSTRACT

The systems model, UTAP, developed for the National Uranium Tailings Program as a tool for predicting the dose risk to human populations due to long-term releases of radionuclides, was applied to the Rabbit Lake tailings site in Northern Saskatchewan. The site is owned by Eldorado Resources Limited. The objective of this study was to investigate the feasibility of modifying the UTAP system model and to make a trial application of it to the Rabbit Lake tailings for four proposed close-out options for tailings decommissioning.

The systems model considers the geochemical evolution of U-238 and Th-232 decay series radionuclides in the tailings pile, the transport of these radionuclides through aqueous and atmospheric pathways, their accumulation in fish, berries and vegetables, and the associated radiological dose to potential human receptors located at a Hidden Bay fishing lodge and at the Wollaston Lake community. The code uses steady-state estimates for the water budget of the tailings and receiving waters for making the calculations, but computes the non-steady state response of the geochemical system of the tailings and the biochemical system of the receiving environments of groundwater and surface water. The code does not predict the rate of tailings consolidation, groundwater flow rates or direction in response to variations in precipitation and permeability of the ground; rather, appropriate assumptions or predictions made by more detailed models, such as those which use the finite-difference or finite-element method, are incorporated. In this study, results from previous studies funded by the Eldorado and the NUTP were used to evaluate groundwater regimes and consolidation aspects.

The SENES Phase III code, UTAP.3, was adapted and revised as appropriate. The groundwater, atmospheric transport and deposition, soil, probabilistic parameter sampling, and other algorithms of UTAP.3 were used. The source term, input data management structure, plotting graphics and lake-embayment algorithms of BEAK (1986; UTAP.SASK) were modified and incorporated. This new code was called UTAP.RAB. The major modifications were to the source term algorithm to consider spatial variability and the inclusion of seven discrete groundwater pathways. The source term was adapted to include horizontal and vertical flow between seven tailings zones (boxes), groundwater flow around a frozen zone of tailings, and specification of tailings boxes as predominantly either fine or coarse in respect to grain size characteristics. Size-

dependent radionuclide and mineral concentrations were assigned to the coarse and fine boxes. Fluxes of radionuclides to the environment were predicted over a 1,000-year time frame, and the environmental pathways algorithms used to predict the resulting changes in radiation dose to human receptors.

Four conceptual tailings decommissioning options were considered in this evaluation:

- o a concave surface only (no cover);
- o a concave surface and 600 mm sandy till cover, 150 mm topsoil and vegetation;
- o a concave surface and a 600 mm soil-bentonite infiltration barrier, 150 mm topsoil and vegetation; and
- o a concave surface and a 600 mm waste rock erosion barrier.

Two potential receptor locations were considered in the study - one at the Wollaston Lake community and one at the Hidden Bay fishing camp. The Wollaston Lake receptor is an average individual among the several hundred residents living year-round in the settlement. The Hidden Bay receptor is assumed to reflect the characteristics of a fishing guide who would live in the camp during summer months and guide anglers from outside the local area.

The radiation exposure pathways considered in this study are inhalation of radon and dust from atmospheric pathways, external exposure to groundshine, drinking of surface water, and consumption of vegetables and berries contaminated by atmospheric dustfall. Unlike other applications of UTAP, consumption of wild animals such as moose and caribou are not considered because they are not routinely hunted within a 50 km distance of the tailings, the limit for calculation of dose from atmospheric pathways.

Hydrologically, groundwater flows from the tailings through seven pathways. Groundwater surfaces at varying distances from the tailings to become seepage streams. Eroded material from the tailings surface is carried by runoff into a "duck" pond. Drainage from the seepage streams and the duck pond flows into one of three receiving waterbodies: Parks Lake, Hidden Bay and Wollaston Lake. Hidden Bay is an embayment of Wollaston Lake and Parks Lake flows via a small creek into Hidden Bay.

These site specific coding aspects were programmed, and a code verification and quality assurance program developed. This included a program designed to ensure the proper passing of information between subroutines, various "white box" and "black box" tests, and walk-throughs.

Several unique features of the Rabbit Lake tailings site were addressed, including:

- o the use of seven boxes in the source term to account for site specific vertical and horizontal variability caused by tailings disposal practices;
- o the consideration of coarse and fine fractions within the tailings and size-dependent radionuclide concentrations on the solids;
- o consideration of a frozen zone in the tailings;
- o provision for seven groundwater pathways which emerge to the surface from the tailings in three directions and at different distances from the tailings;
- o model calibration using:
 - laboratory measurements for the linear distribution coefficient (K_D), and
 - observed aqueous concentrations in the tailings porewater and in seepage from the dams; and
- o the hydrologically-coupled nature of Hidden Bay and Wollaston Lake.

To aid characterization of these features, new data were developed in an allied set of special studies (BEAK, 1987), funded by Eldorado Resources Limited. These studies which further characterized the physics and hydrogeology of the tailings and geochemical aspects of the solid-porewater distribution of radionuclides, included:

- o A groundwater flow study;
- o Chemical measurements of tailings porewater;
- o Mineralogy and solid phase identification of tailings solids;
- o A chemical washing study;
- o A Ra-226 nuclear emulsion study; and
- o Adsorption (K_d) measurements upon geological materials of receiving groundwater environments.

The computer code uses a set of data, some of which are site-specific, and some of which are from the literature. Tailings-specific, radionuclide concentrations and flow pathways are estimated using the results of previous work, the special studies, and some assumptions. Groundwater characteristics are site-specific and derived from separate site investigations. Values for specific groundwater and tailings coefficients (coprecipitation coefficients and K_D values, respectively) were set using calibration studies. Input data for the atmosphere and lake pathways are site-specific for those parameters for which site-specific data were available. Meteorological data from Collins Bay were used for the atmosphere transport model. Morphometric and hydrological data for the lakes are site-specific, while kinetic coefficients for internal lake processes (e.g., sediment-water transfer) are based on the literature. Bioconcentration data from lakes in Saskatchewan were assessed using histograms and probability plots to develop distribution data for BCF values. Site-specific characteristics and results of discussions with Wollaston Lake residents were used to estimate food consumption habits at potential receptor locations. Standard dose conversion factors were applied in the dosimetry modelling. The dose conversion factor value used for thorium ingestion was based on the latest gut-to-blood transfer factor derived for thorium isotopes by Atomic Energy of Canada Limited.

The results of this study demonstrate the applicability of UTAP and provide direction for further work. The general systems model (UTAP) can be readily adapted and applied to a tailings site and used for evaluation of proposed decommissioning options. New applications should develop site-specific data for as many parameters as possible and use literature data for the remainder. Code modifications may be required; priorities of modification should be the source-term, coding which directs the routing of water transport of contaminants, and component pathway models.

For the Rabbit Lake site, model calculations indicate the following. The calculated geometric mean dose rate received by each potential receptor is approximately constant for the first several hundred years, after which it increases by three to four times at 600 years in the future. This is caused by washout of the mineral phase controlling Ra-226 in the tailings area directly adjacent to the south dam, and a lack of a compensating increase in sorption mechanisms in the dam material comprised of local till, waste rock, and recycled tailings.

The main pathways contributing to the predicted future radiological dose rate are consumption of drinking water and consumption of fish from the lake. The dose rate from atmospheric pathways is over two orders of magnitude lower. Pb-210 and Ra-226 generally make the largest contribution to dose, but Th-230, total uranium and Po-210 each make a contribution to dose generally within an order of magnitude of that of Pb-210. The dose for the Hidden Bay receptor and Wollaston Lake receptor are similar, despite a 20 km distance separating them, because the predicted radionuclide activity in the lake and bay are similar due to lake-embayment mixing.

Values of the dose rate for the two receptors are given in this report, and a comparison of the dose rate is given with that from natural sources. The calculated future values are of the order of 1 to 10 uSv/year. Care should be taken in quoting these values with much veracity because the calibration used in the model requires further study. In particular, the calibration for the mechanisms controlling Th-230, Ra-226 and Pb-210 in the source term and in the groundwater pathways should be checked with additional field data. Further calibration studies may result in different dose estimates being calculated.

Sensitivity analysis and inspection of the model assumptions suggest priorities for further work. Additional laboratory measurements are needed to evaluate adsorption coefficients, particularly for Th and Ra-226 as a function of ion exchange phenomena and varying solution conditions in geological media. Additional porewater measurements are required to confirm the recalibration of the coprecipitation distribution coefficient obtained for Ra-226. Additional field measurements of Th-232 in porewater and associated anions (F^- , SO_4^{2-}) are required to evaluate the solubility constant for thorium oxide in the tailings pile. Additional mineralogical studies are required to confirm that thorium oxide is the phase controlling Th-230 behaviour in the tailings. Additional groundwater studies are required to evaluate long-term water levels and flow rates from the decommissioned tailings. Additional field studies would be useful to provide calibration data for evaluation of the sediment-water portion of the lake model.

Analyses of the model also indicate that bioconcentration factors for Ra-226 and Pb-210 in fish are influential in dose calculations. The values developed in this study from northern Saskatchewan data are the most up-to-date. Any further improvement in the data set would require an extensive set of new data.

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1.0 INTRODUCTION, SCOPE AND OBJECTIVES

The National Uranium Tailings Program (NUTP) was formed to conduct research into long-term environmental behaviour of uranium mill tailings. The main objective of the NUTP is to provide a scientifically credible information base upon which decisions can be made, with a known degree of confidence, in establishing reasonable criteria for the protection of the environment and which can also be used to propose practical guidelines for uranium tailings management. One part of the research of the NUTP is the development and demonstration of a probabilistic assessment of the long-term effects of uranium mill tailings upon the environment and upon humans.

Uranium mill tailings are a potential environmental concern both from the perspective of long-term exposure to low level radiation and the ongoing discharge of non-radioactive contaminants from these tailings. The future behaviour of these tailings is difficult to predict and, without protective measures, increased and possibly unacceptable discharges of contaminants may occur in the future due to biological, chemical or physical changes within the tailings mass and its immediate environment. Many of these processes were not previously well understood. Fundamental research, funded by the NUTP, the Atomic Energy Control Board and National Science and Engineering Research Council, have increased our understanding of some of these processes. One of the prime foci of the NUTP has been predictive modelling using probabilistic assessment techniques. This has substantially increased our understanding of the interaction of many of these processes and the environmental consequences. Predictive modelling can assist in the understanding of tailings behaviour with different protective measures in place so that regulatory agencies or mine operators know how to close out tailings areas in a manner which will be environmentally sound into the foreseeable future.

The NUTP has previously contracted:

- o SENES Consultants Limited (Willowdale, Ontario) to develop and demonstrate a probabilistic assessment of a reference site typical of the Elliot Lake area, and
- o BEAK Consultants Limited of Mississauga to demonstrate a probabilistic assessment of a tailings site typical of the arsenic-and nickel-rich ores associated with the Athabaska Sandstones of northern Saskatchewan.

The objective of this present study is to apply the NUTP probabilistic system model (UTAP) to the Rabbit Lake Uranium Tailings site in northern Saskatchewan.

The specific objectives of this study are:

- o to review the Rabbit Lake site and to abstract it into a format suitable for application of UTAP;
- o to review and to revise, as necessary, existing competent models of UTAP;
- o to apply UTAP to the Rabbit Lake tailings for a basic design for decommissioning and 3 management options; and
- o to assess the results and evaluate future needs for research and data gathering for an environmental assessment and a refined application of UTAP to the Rabbit Lake site.

At the start of this study, as well, it was determined that there were inadequacies in the database for formulating the source term model. Accordingly, in an allied study funded by ELDORADO RESOURCES LTD., the owners of the Rabbit Lake site, several special studies were initiated. They are as follows:

- o Groundwater Flow Study;
- o Chemical Measurements of Tailings Porewater;
- o Mineralogy and Solid Phase Identification of Tailings Solids;
- o Chemical Washing Study;
- o Ra-226 Nuclear Emulsion Study; and
- o Adsorption (K_d) Measurements Upon Geological Materials of Receiving Groundwater Environments.

These studies have been carried out in parallel with the work of this project. Results from these studies available at the end of February 1986 have been incorporated into the modelling work of this project. The results of these studies are incorporated into BEAK (1987) as a separate report to Eldorado Resources Ltd. Relevant measurements are incorporated into this report, especially in Chapters 3.0 and 4.0, and Appendix B.

In this project, the radiological consequences to humans and the environmental concentrations resulting from wind-driven transport, surface water erosion and

groundwater seepage are evaluated using UTAP. The radiological consequences and environmental concentrations are evaluated using Monte Carlo simulation to give probabilistic information for the model's calculations. Monte Carlo simulation involves repeated calculations of a deterministic simulation model to give probabilistic estimates of dose or concentration.

Other management issues, including geotechnical issues such as the rate of tailings consolidation and dam stability, are not addressed in this project. Effects such as erosion by wind and water are considered in the manner that they effect environmental concentrations but very detailed models for describing the rate of development of gullies and other phenomena related to geotechnical stability and integrity of the tailings are not used in a predictive manner. These issues are not considered due to the objectives of this study and the capabilities of UTAP - UTAP is constructed to predict and to evaluate radiological consequences, not to predict geotechnical stability. Similar to questions of groundwater transport, where finite difference models were used to predict groundwater flow and then the results assimilated into UTAP, other more detailed models are required to predict aspects of geotechnical stability. Then, these results would be aggregated into a format for incorporation into UTAP.

2.0 CHARACTERISTICS OF RABBIT LAKE SITE AND RECEIVING ENVIRONMENTS

2.1 Site Location and General Site Description

The Rabbit Lake tailings area is located approximately 3000 metres south of the Rabbit Lake mill and about 600 metres west of the northern end of Parks Lake (Figure 2.1). Tailings are located in a north-south trending valley enclosed on the east and west sides by ridges rising approximately 30 metres above the valley floor. The east ridge is quite steep and separates the tailings area from Parks Lake. The western ridge is more gradual in slope and separates the area from a higher valley to the west. A study carried out by GEOCON (1972), described the area prior to development. The east and west ridges which bound the site are comprised of bedrock which consists of an assemblage of gneisses, quartzite, pegmatite and amphibolite, with secondary (fracture) permeability ranging over four orders of magnitude, from 10^{-7} at depth to 10^{-3} cm/sec near the surface (GEOCON, 1982). Prior to development, the site was covered by sparse vegetation, although on the high ground there was some tree cover. Overburden in the area consisted of a veneer of glacial till 5 to 6 metres in depth, topped by 0.3 to 1 metres of muskeg. The basal till tends to be silty to sandy in nature with permeability ranging from 1×10^{-5} to 3×10^{-3} cm/sec and the ablation till consists of a gravelly-cobbly material with permeability generally in the 10^{-2} cm/sec range (Gulf Minerals, 1980). Except for the foundation limits of the dams, this muskeg was not removed from the bottom of the tailings area.

As developed, the catchment area of the entire basin, including tailings deposition area and the precipitation ponds, is 66 ha. A portion of this area was removed from contributing to the basin runoff by the construction of a diversion channel along the foot of the west ridge. The surface area of the tailings in the basin was 55 ha at completion. The final deposition of tailings to the area was 5.9×10^6 tonnes (Table 2.1). The maximum elevation of tailings at the cessation of deposition prior to consolidation was 448 metres. Tailings were placed to a mean depth of 25 metres by the end of operations.

2.2 Operating History and Disposal Geometry

Tailings were discharged from points located along the north and south dams and along the east ridge. The discharge points were moved periodically to provide an even

FIGURE 2.1: RABBIT LAKE TAILINGS AREA

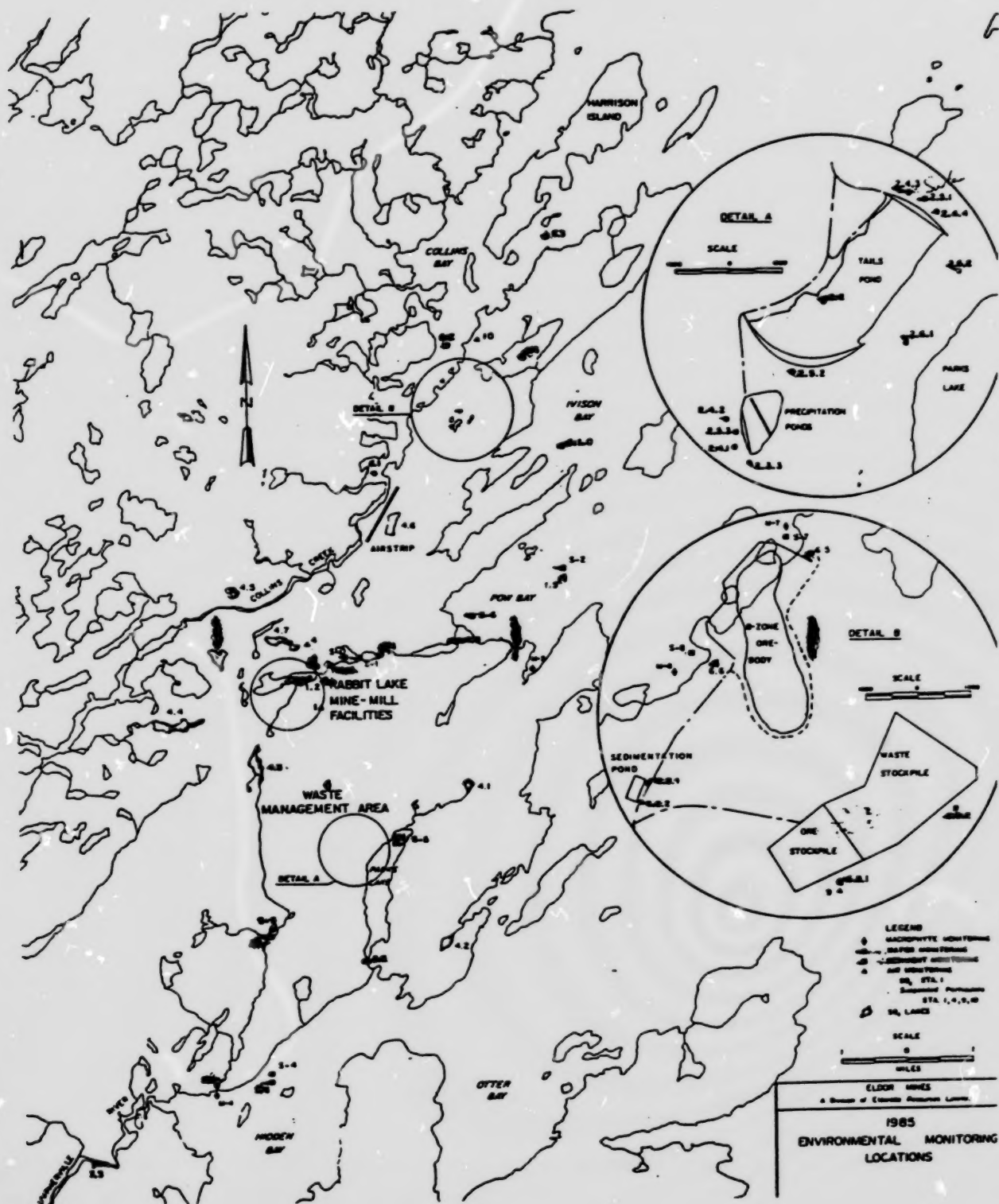


TABLE 2.1: MILLING RATE RECORD

Year	Mill Throughput (tonnes)
1975	130,000
1976	397,000
1977	547,000
1978	573,000
1979	650,000
1980	666,000
1981	677,000
1982	616,000
1983	620,000
1984	642,000
1985	404,000
	5,922,000

distribution of tailings within the basin. The system operated so that a decant pond was maintained in the west central region of the tailings area (Figure 2.1).

The predominant point of discharge of the tailings slurry was located on natural high ground near the west end of the North Dam. Winter discharge in particular, was almost entirely from this point. Prior to 1980, a mobile cyclone was operated intermittently on the South Dam to provide coarse tailings for building up the south dam. The fine fraction of silty tailings (slimes) from the cyclone were deposited immediately upstream of the South Dam. End discharge from points located on the South Dam was undertaken periodically from 1979 to form a beach against the dam. Periodic end discharge from various points on the east side of the tailings impoundment area was carried out after 1981.

This manner of tailings deposition resulted in a tailings pond occupying essentially the southern half of the site with standing water against the South Dam for most of the period up to 1979. Since then, the southern limit of the tailings pond was displaced by tailings deposition near the South Dam and resulted in its more central location.

During operation, tailings pond water was decanted at 76 L/s from a pump barge located on the west side of the pond. After barium chloride addition for radium precipitation the decant was directed to the first of two precipitation ponds located downstream of the south dam. (These ponds are still in operation.) Following settling in the first pond, the water overflowed into the second pond prior to discharge from the effluent weir. To eliminate short circuiting, the first precipitation pond contained one baffle; and the second, four. The overall retention time is estimated to have been 12 days by volume. In 1978, a polymeric flocculant addition system was added to further improve the precipitation of radium-barium sulphate floc.

During the later years of operation, three experimental sand filters were installed to treat a portion of the final precipitation pond effluent. As part of the B-zone mine expansion, four additional filters were installed to permit filtration of 100% of the B-zone mill effluent. The system was started-up and tested in 1984 and has run continuously since.

At the end of tailings deposition in October 1985, the surface of the tailings area was generally concave. Tailings are at a higher elevation at the north and south dams and along the east and west walls of the valley than at the centre in the location of the barge pump. The total difference in elevation is approximately 3 metres prior to consolidation (Figure 2.2). As shown in the figure, sand and slimes tailings have deposited in different areas due to their settling characteristics. The frozen tailings at the North dam result from the winter deposition of tailings almost exclusively from the North dam.

2.3 Surface Water Hydrology

The runoff characteristics of the tailings area controls the partitioning of hydrological pathways between groundwater and surface water. This influences the estimation of the mass of radionuclides exported from the tailings surface under the decommissioning scenarios, and the flux of radionuclides out to receiving waters.

The Rabbit Lake tailings area is located in a natural saddle or local drainage divide. Prior to the deposition of the tailings, surface water flowed south to the effluent stream and north and east through a wetland area to the head of Parks Lake. Both the effluent stream and Parks Lake eventually drain into Wollaston Lake at Hidden Bay (Figure 2.3). Following development, the construction of the north dam precluded surface flow to the north. However, seepage flows exiting the base of the north dam follow the same course north and east to Parks Lake.

The remainder of the immediate area is drained by other tributaries of the effluent stream all of which are characterized by small headwater lakes and short irregular channels.

The drainage pattern of the tailings area itself is well defined. The area is bounded on the east and west by natural ridges and on the north and south by the earthen dams. Runoff contribution from areas outside the immediate tailings area to the surface drainage of the tailings is not significant given that the total catchment area contributing to the tailings pond is 66 ha and the tailings surface area is 55 ha.

Peak runoff rates influence the potential extent of erosion and gullyng of the surface. Peak runoff could occur as a result of either a combination of rainfall and snowmelt in

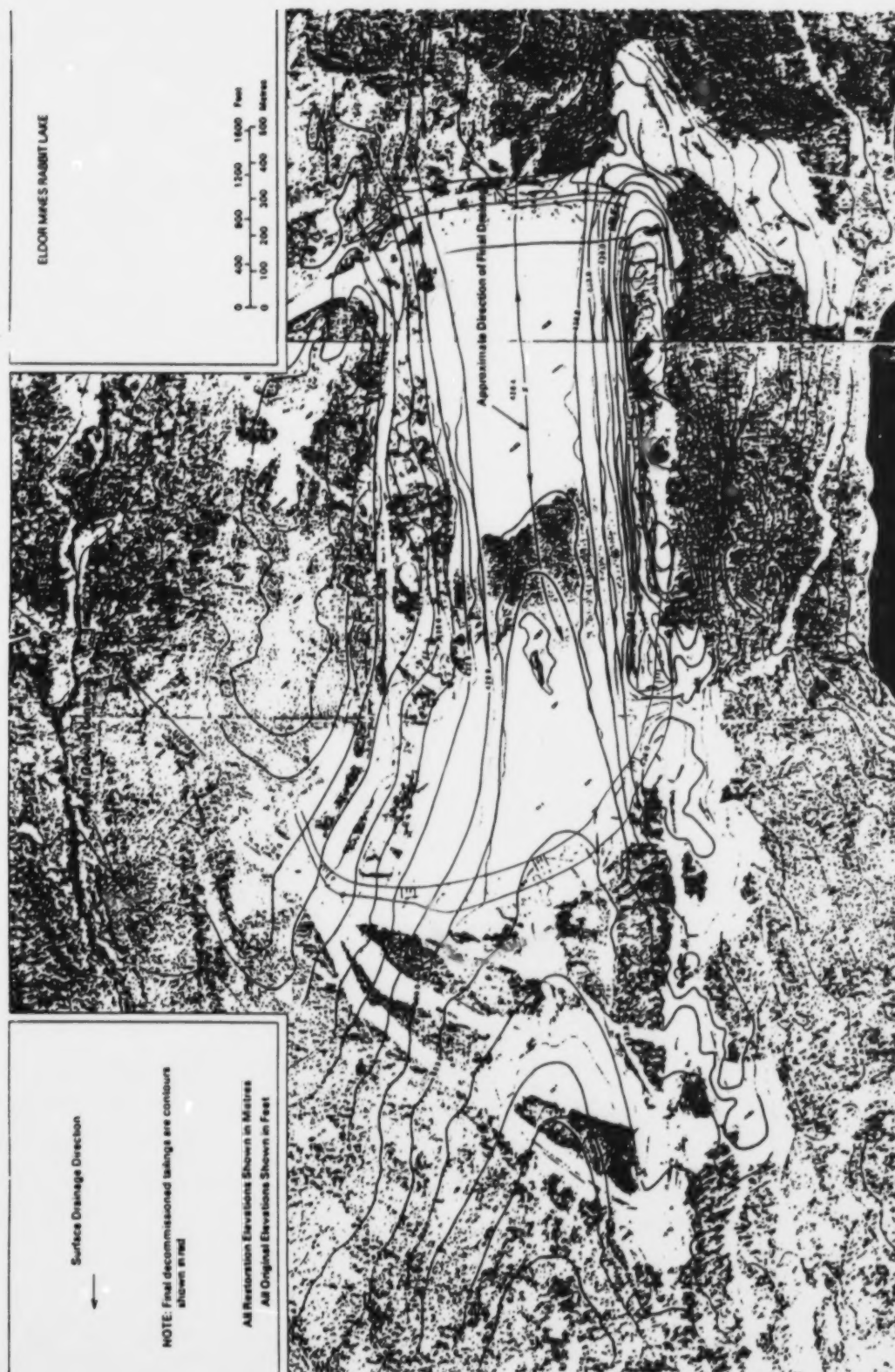
FIGURE 2.2:

RABBIT LAKE TAILINGS FEATURES



FIGURE 2.3:

SURFACE DRAINAGE PATTERN OF RABBIT LAKE TAILINGS



May or a summer rainstorm during the period June to September. Because of the small catchment area, it is expected that maximum runoff rates from the tailings area will be due to rainstorms. Only in larger drainage areas would snowmelt be expected to cause an equal peak to that of rainfall. However, spring flows should typically result in the greater volume of runoff than summer storms due to accumulated snow.

No continuous runoff measurements exist for the tailings area. Outflow from the precipitation pond was measured during operation but depended on the pumping rate, which in turn was governed by operational factors. Since flow information was required for the probabilistic analysis, runoff estimates were obtained transposing calculated unit runoff rates from other areas and previous studies (Section 3.2).

2.4 Tailings Characteristics

2.4.1 Physical Characteristics

The peripheral deposition method described previously has resulted in both horizontal and vertical differentiation of tailings types within the basin. Sand size tailings grains settled near the points of deposition while the finer, silt and clay sizes were carried further into the basin to the vicinity of the decant barge pump and base of the South Dam. Therefore, the tailings particles at the periphery of the area are generally larger than the grain sizes in the central portion of the area. The transition from the coarser tailings to the finer sizes is not a distinct one. Rather, the lenses of sand and silt sized tailings are intermingled because of the periodic relocation of the discharge point. A study by GEOCON (1986) reported in detail on the characteristics of the tailings.

Geocon reported on three boreholes put down in the winter of 1986 while working from the frozen tailings surface. Hole NUTP-S1 was located in the vicinity of the North dam and revealed the existence of predominantly frozen tailings for much of the profile at that location (Figure 2.2). This is probably because tailings were generally discharged from the North dam during the winter months to reduce the pumping distance and the risk of freezing and rupture of the pipeline. Ice was encountered in both horizontal lenses and vertical fissures within the profile. Tailings were visibly stratified into random horizontal sand and silty fractions.

Borehole NUTP-S2 was located in the vicinity of the South dam where the tailings were essentially ice-free for much of the depth, except for an upper crust of frozen tailings. The tailings were also stratified in this area but more so than in NUTP-S1. The tailings were sandier at depths less than 9 m (elevation 439.5 m) than deeper depths.

Borehole NUTP-S3 was located within the clarification pond which at that point was approximately 4 m deep. Tailings in this area were predominantly silty (slimes). However, pronounced stratification between silty and sandy layers was again observed.

Detailed tailings characterization tests were carried out by GEOCON (1986). Both the existing in situ and the anticipated values of the parameters after consolidation were investigated (Table 2.2). It is notable that 5 m of consolidation is predicted, resulting in a significant change in all of the parameters used to describe the tailings. It is also interesting to observe that there is little difference in the wet bulk densities of the slimes and the sand tailings although the dry bulk densities show a marked increase for the sand fraction after consolidation. This feature and the difference in the moisture content of the tailings at different locations represent the only significant variation in the characteristics of the sands and slimes.

2.4.2 Chemical and Radiological Characteristics

The tailings deposited in the Rabbit Lake tailings area originated from the milling of ore mined from the Rabbit Lake open pit. A minerological analysis of that ore reveals it to be high in uranium. No thorium or arsenic was found (Table 2.3) by Ruzicka (1986), but thorium was found by BEAK (1987) and ELDORADO (1986) (see Table 3.1.1). It should be noted that these analyses of Ruzicka were carried out to determine the relative percentages of elements for mining and milling purposes. In this type of analysis, small proportions of elements may not be detected.

The average ore grade milled during the operation of the Rabbit Lake pit was 0.37% (U_3O_8) and the average recovery was 91.3%. Thus, the tailings have been estimated to contain an average uranium content of 0.032% (U_3O_8) or approximately 270 ug/g U (MacLaren Engineers/Geocon, 1984). In addition, if secular equilibrium is assumed, the radium content of this ore is 38 Bq/g and since only minimal removal is achieved in milling, the radium content in the tailings would also be 38 Bq/g. Other radionuclides,

TABLE 2.2: PHYSICAL PROPERTIES OF RABBIT LAKE TAILINGS

Property	In Situ Value	Post-Consolidation Value
Total Mass		$5922 \times 10^6 \text{ kg}$
Total Area - Tailings		$550,000 \text{ m}^2$
Total Area - Drainage Basin		$660,000 \text{ m}^2$
Average Length Tailings		1800 m
Average Width		305 m
Average Depth	25 m	20 m
Porosity - Slimes	0.65	0.55
Porosity - Sands	0.63	0.55
Specific Gravity - Slimes	(2.53 - 2.69)	2.61
Specific Gravity - Sands	(2.54 - 2.61)	2.58
Wet Bulk Density - Slimes	(1220 - 1730) 1530 kg/m^3	1690 kg/m^3
Wet Bulk Density - Sands	(1440 - 1720) 1570 kg/m^3	1680 kg/m^3
Avg. Moisture Content - Slimes	(47.5 - 175.3) 98.1%	47%
Avg. Moisture Content - Sands South	(33.8 - 88.5) 66.0%	47%
- Sands North	(50.9 - 207.6) 93.3%	-
Dry Bulk Density - Slimes	(582 - 1172) 820 kg/m^3	1150 kg/m^3
Dry Bulk Density - Sands	(767 - 1282) 920 kg/m^3	1140 kg/m^3
Void Ratio - Slimes	1.8	1.2
- Sands	1.8	1.2

Definitions

$$\% \text{ Moisture} = \frac{\text{Weight Water}}{\text{Weight Solids}} \times 100$$

$$\text{Porosity} = \frac{\text{Vol. of Voids}}{\text{Total Volume}}$$

$$\text{Void Ratio} = \frac{\text{Vol. of Voids}}{\text{Vol. of Solids}}$$

After GEOCON (1986)

TABLE 2.3: MEAN ELEMENTAL CONSTITUENTS IN GRAB SAMPLES - RABBIT LAKE DEPOSIT (all values in %) (after Ruzicka, 1986)

Constituent	Value	Constituent	Value
Si	-	Cr	0.009
Al	4.3	Cu	0.024
Fe	3.8	La	-
Ca	-	Mo	-
Na	-	Nd	-
Mg	4.6	Ni	0.011
Ti	0.24	Pb	0.316
P	-	Sc	0.005
Mn	0.10	Sr	0.011
Ag	-	Th	-
As	-	U	3.44*
B	0.024	V	0.028
Ba	0.017	Y	0.029
Be	0.002	Yb	0.003
Co	0.003	Zn	0.024

* Average value of nine samples with values ranging from 0.13 to 17.9%. The mean ore composition ultimately milled was 0.31% as U.

TABLE 2.4: RADIOLOGICAL CONSTITUENTS OF RABBIT LAKE TAILINGS
(after ELDORADO, 1986)

Sample Description	U ug/g	$^{238}\text{U}^*$ Bq/g	^{230}Th Bq/g	^{226}Ra Bq/g	^{210}Pb Bq/g	^{210}Po Bq/g	^{232}Th ug/g	Bq/g
Coarse Material	300 $\pm$ 10 240 $\pm$ 30	3.7 3.0	12 $\pm$ 1 14 $\pm$ 1	9.6 $\pm$ 0.8 7.4 $\pm$ 0.6	13 $\pm$ 1 12 $\pm$ 1	11 $\pm$ 1 14 $\pm$ 1	13 $\pm$ 10	.053
Fine Material	280 $\pm$ 28 300 $\pm$ 30 350 $\pm$ 40	3.5 3.7 4.3	43 $\pm$ 4	58 $\pm$ 5 59 $\pm$ 5	48 $\pm$ 5 46 $\pm$ 5	43 $\pm$ 4 89 $\pm$ 9	24 $\pm$ 10	.09
Tyler Screen Fractions (x = um)								
1700 x 600		15 $\pm$ 2	10.7 $\pm$ 0.9	18 $\pm$ 2	17 $\pm$ 2			
600 x 300		12 $\pm$ 1	7.6 $\pm$ 0.6	13 $\pm$ 1	13 $\pm$ 1			
300 x 150		10 $\pm$ 1	6.3 $\pm$ 0.6	10 $\pm$ 1	14 $\pm$ 1			
150 x 75		12 $\pm$ 1	6.2 $\pm$ 0.5	12 $\pm$ 1	18 $\pm$ 2			
75 x		18 $\pm$ 2	15.6 $\pm$ 1.2	22 $\pm$ 2	24 $\pm$ 2			
Calculated Composite Analysis Based on % Weight Fraction								
		12.0	7.8	12.9	15.4			

* Calculated on the basis of 12,358 Bq ^{238}U /mg U.

Th-230, Pb-210 and Po-210, are expected to remain in the tailings in similar concentrations. These calculations show reasonable agreement with the analysis reported in 1986 by ELDORADO (1986), in Table 2.4, recognizing that these radionuclides tend to concentrate with the fines.

These analyses were carried out on both the coarse and the fine material (Table 2.4). As is usually considered to be the case, radium was found to be in higher concentration in the fine material than in the coarse. The same was true for thorium-230, lead-210 and polonium-210. Uranium was found to be in approximately equal concentration in both size fractions.

Stable elements were also determined in the 1986 study. Sulphur as sulphate, and calcium results suggest that higher concentrations can be expected in the finer fractions although few samples were analyzed (Table 2.5).

The tailings mass exhibits a neutral to slightly acidic pH, as indicated by the barge pump discharge which averages a pH of 7.7 and seepage which averages 6.8 to 6.9 (MacLaren Engineers/ GEOCON, 1984).

2.5 Containment Dams

Two containment dams were built at the north and south ends of the valley to enclose the tailings basin (Table 2.6). Materials for the dam were mainly locally borrowed fill, but cycloned coarse tailings were also occasionally used. Both the north and south dams were raised by the fixed centreline method of staged construction, until 1979 when this was changed to the downstream method of construction with a fixed crest width of 6 m. The starter dams were constructed in 1974 and deposition of tailings into the area began in late 1975. Raising of the dams was carried out annually from 1977 to maintain a minimum freeboard of 1.5 m (Table 2.7). Any extra crest width required to facilitate construction activity on the south dam was provided by construction on the upstream side of the crest, over tailings (GEOCON, 1980). For the north dam, it was not necessary to provide additional crest width although it was necessary to flatten the downstream slope to 2H:1V for long-term stability. The original design of the tailings retention dams indicated a maximum crest elevation of 445 m (1460 ft). However, due to lower bulk densities achieved in deposition than those originally estimated, an additional 4.6 m of dam height was required to bring crest elevations to 450 m (1475 ft).

TABLE 2.5: CHEMICAL CHARACTERISTICS OF RABBIT LAKE TAILINGS
(after GEOCON, 1986)

Constituent (Units mg/g)	Coarse Fraction	Fine Fraction
Mg	70±7	68±7
Ca	12±9	66±5
Na	0.64±0.10	0.58±0.09
K	1.0±0.1	1.2±0.1
Fe	24±2	22±2
Al	51±5	51±5
S	12.3±0.3	69±3
SO ₄ **	36.9	207
CO ₃	7.5±0.9	-
Cl ⁻	0.4	0.6±0.1

** Calculated on the assumption tht all S in tailings is present as SO₄²⁻, in which case there are 2.9959 mg SO₄²⁻ /mg S.

TABLE 2.6: CONTAINMENT DAMS CHARACTERISTICS

	North Dam	South Dam
Final Crest Elevation 1983 (m)	449.7	449.7
Final Crest Length 1983 (m)	579	1057
Original Ground Elevation (m)	427	425
Upstream Slope (Horiz/Vert)	2:1	2:1
Downstream Slope (Horiz/Vert)	2:1	2:1
Estimated Volume of Fill (m ³)	322,000	574,000

TABLE 2.7: HISTORY OF DAM CONSTRUCTION

Year	Crest Elevation (m)	
	North Dam	South Dam
1974 (Starter Dams)	433.8	433.5
1977	437.5	436.6
1978	440.5	439.0
1979	440.8	440.8
1980	443.0	443.0
1981	445.1	445.1
1982	447.4	447.4
1983 (Final Elevation)	449.7	449.7

The dams were constructed of silty and sandy till. Free-draining sandy till was used for downstream construction while less permeable silty till (20% minus 200 mesh) was used mainly in the upstream portions of the dams for seepage control. Cycloned tailings were used until 1980 for construction of the western portion of the south dam for approximately two-thirds of its length. The balance of the dam was completed using till borrow material.

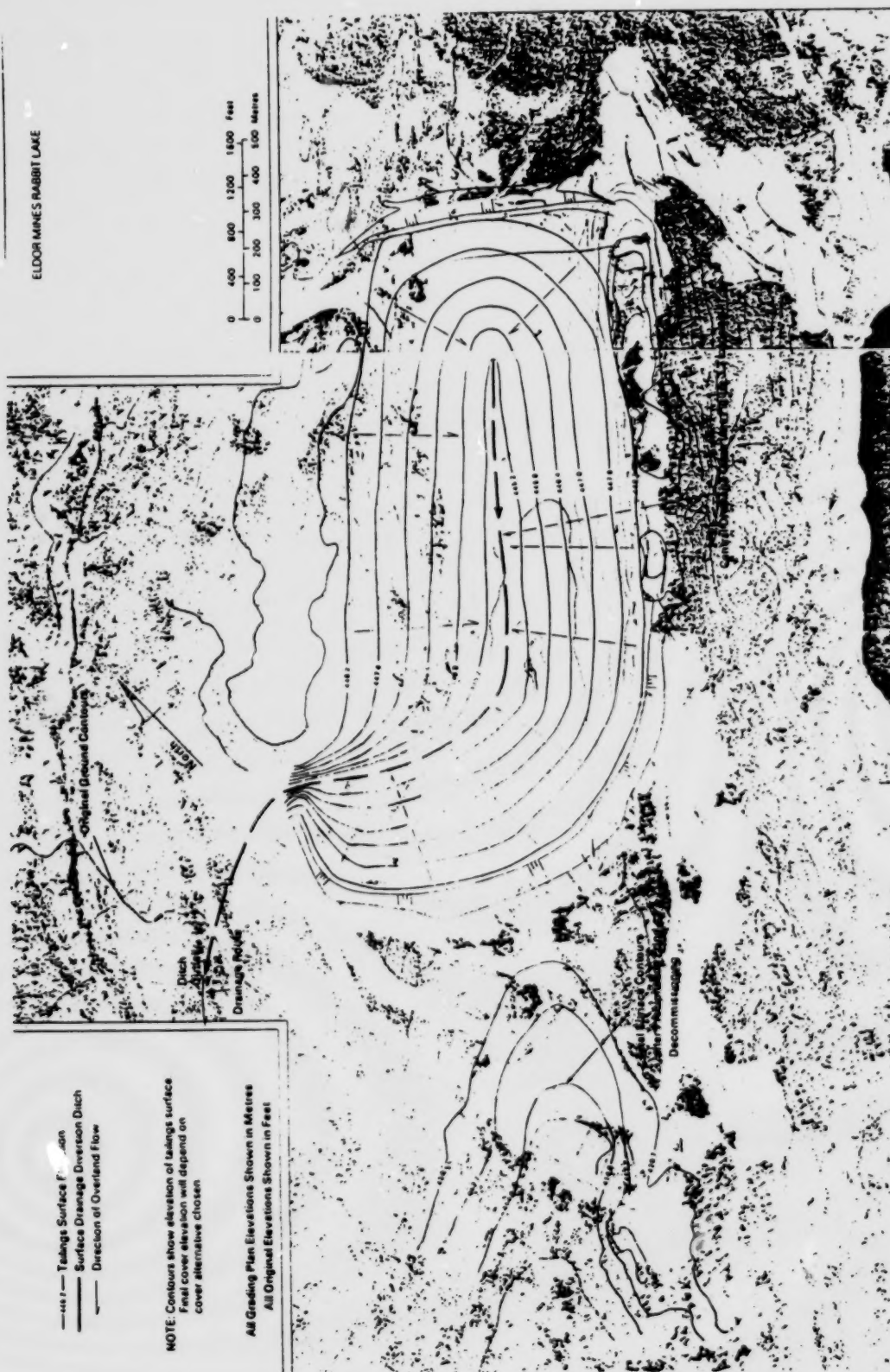
Both of the retention dams were founded on competent till with cut-off keys installed to bedrock along the foundations and the abutments. Seepage control and pressure relief inside the dams are provided by a series of finger drains of coarse, free draining material installed perpendicular to the dam centre-lines. Seepage exits via these finger drains into seepage collection ditches at the downstream toe of each dam. At the south dam, this seepage is routed directly to the precipitation ponds where it is treated with barium chloride. North dam seepage undergoes no treatment and meanders through a boggy area, eventually discharging to Park's Lake.

The dams have been analyzed for their stability using standard slip surface stability analysis. These analyses were carried out for the 1979, 1980, 1981 and maximum crest elevations (GEOCON, 1980). The method, which included fill characteristics in the calculation, showed that the factors of safety varied from 1.58 to 2.39. In their classic work on soil mechanics Terzaghi and Peck (1967) determined that a value of 1.5 was adequate and this factor of safety has become an industry standard. Since the existing structures exceed this value, their long-term stability is considered to be satisfactory.

2.6 Close-Out Options

Cost-benefit analyses carried out in two studies indicated that the most cost-effective closed out tailings surface shape was concave (MacLaren Engineers and Geocon, 1984 and MacLaren Plansearch, 1986). This shape is characterized by high tailings elevations at the periphery of the area and low elevation in the centre (Figure 2.4). The area slopes at approximately 1% from the periphery to the central channel which is designed to carry the runoff from a precipitation event with a return period of 100 years. This flow exits the tailings via a spillway excavated through the west ridge near the west abutment of the south dam. To prevent gully erosion, the channel is constructed with the same 1% sideslopes as the tailings surface.

FIGURE 2.4 POST-CLOSURE CONFIGURATION OF RABBIT LAKE TAILINGS



Although the shape of the surface at the end of deposition was approximately concave, it would require extensive re-shaping to achieve the desired concave shape with a central channel. Tailings from areas higher than required would be relocated to the low area in the vicinity of the pump barge. Prior to the reshaping operation the surface of the tailings would be permitted to drain and desiccate to allow construction equipment to travel safely on the surface. This reshaping of the tailings area would result in the deposition of approximately 3 m of sand tailings over the finer slimes in the centre of the area.

Following decommissioning of the tailings, approximately 5 m of consolidation is expected. The resulting shape would be similar to the designed concave shape, but care would have to be taken in the design of the concave shape to ensure that after consolidation, the area would continue to be free-draining.

For this modelling study, the results of the studies referred to above were considered in the selection of close-out options for analysis. Accordingly, a concave surface shape with the following four cover options are examined in this study:

- Case 1: Base case - shaped surface, no cover;
- Case 2: 600 mm sandy till cover, 150 mm topsoil, vegetation;
- Case 3: 600 mm soil-bentonite infiltration barrier, 150 mm topsoil, vegetation; and
- Case 4: 600 mm waste rock erosion barrier.

Cover material characteristics are as follows:

<u>Property</u>		<u>Value</u>
Sand-Till	- Specific Gravity	2.1
	- Dry Porosity	0.27
	- Moisture Content	5%
Soil-Bentonite	- Specific Gravity	2.1
	- Dry Porosity	0.3
	- Moisture Content	7%
Waste Rock		NA

The base case is the standard case in which the tailings are contoured to a 1% slope and from which dust and water erosion and radon exhalation occurs, unhibited by any cover, except for natural vegetation which is assumed to cover the tailings in the future.

Scenarios 2 and 3 will control wind and water erosion and minimize radon transport. Scenario 3 will be somewhat more effective for minimizing radon exhalation due to the higher moisture content of clay. Scenario 4 will minimize dust and water erosion, but have a smaller impact upon radon exhalation than Scenarios 2 and 3.

2.7 Meteorology and Climatology

The meteorological and climatological characteristics of an area must be considered when evaluating the design of a decommissioned tailings area. Information on the wind and mixing characteristics of the lower atmosphere are required to estimate the dispersion and concentration of airborne radionuclides for subsequent pathways analysis.

The meteorological and climatological aspects of the Rabbit Lake air environment are best represented by the Collins Bay Airport (A) meteorological station located at the mill site, and approximately 3 km north-east of the tailings area. This station is maintained by the Atmospheric Environment Service (AES) and has been operated by trained personnel since 1972 recording temperature, precipitation and wind data. Additional factors including frost and snow cover are available from other nearby AES stations such as Uranium City, Cree Lake, Lynn Lake and Ennadai Lake and from privately-owned weather stations such as McClean Lake. Data from the Collins Bay station were used to provide meteorological input data for the UTAP Model. These data are described in detail in Appendix D. A brief description of the local climate is provided here.

The Rabbit Lake tailings area is located in the continental sub-arctic region of Northern Saskatchewan. The climate of the region is characterized by short cool summers and cold winters. The mean daily temperature is -4.1°C . July is the warmest month with a mean daily temperature of 15.0°C , while the coldest month is January with a mean daily temperature of -25.1°C . The extreme temperatures observed at the Collins Bay weather station range from a low of -42.0°C to a high of 30.1°C . Mean daily maximum temperatures of the warmest months are below 20°C and only three months have mean

daily temperatures of 10° C or more. The winters are cold and dry and the mean daily temperatures of the coldest months are below -20° C. Freezing of Wollaston Lake in most years begins in November and breakup occurs around the middle of June. The average frost free period is approximately 90 days.

Collins Bay precipitation data show that the area is characterized by high precipitation in early summer and low precipitation in late winter. Total monthly rainfalls of greater than 1 mm may be expected in each month between April and November, with a maximum mean monthly rainfall of 106 mm (4.17 in) occurring in July. At Collins Bay, the maximum snowfall of 47 cm (18.5 in) occurs in October, with a monthly average of 30.8 cm (12.1 in). Based on these data, Rabbit Lake annually receives 546 mm (21.48 in) of total precipitation, 354 mm (13.92 in) as rain and 192 cm (7.56 in) water equivalent as snow. Approximately 144 days per year have measurable precipitation (0.2 mm as water).

2.8 Subject Populations

The populations used in the probabilistic calculations of impact are:

- o the Wollaston Lake community on the eastern shoreline of Wollaston Lake, and
- o the Hidden Bay Lodge.

Wollaston Lake represents the closest permanent population in the area. The Hidden Bay receptor consists of staff members of the Hidden Bay Lodge who are assumed to be in residence for a total of about five months annually from spring to fall.

The 500 individuals living at Wollaston Lake procure their red meat from sources outside the study area and these are therefore unaffected by any emissions from the decommissioned site. Vegetables are assumed to come from local gardens. Locally picked berries are utilized in the diet to the extent of about 5.5 kg/a per person. Whitefish is a major portion of the local diet and for the purposes of modelling, each individual is assumed to consume about 100 kg per year. Drinking water is taken from Wollaston Lake.

The residents of Hidden Bay Lodge are assumed to consume game fish (primarily lake trout) from both Hidden Bay and Wollaston Lake proper, and to drink their water from the Bay. A few local berries are assumed to be picked and consumed, but other components of the diet are assumed to come from outside of the study area. Moose and caribou, although regularly consumed by Wollaston Post residents, are not hunted locally. Caribou are hunted near the junction of the Saskatchewan-Manitoba-Northwest Territories borders, and moose are taken at considerable distances (about 80 km) from Rabbit Lake, beyond the distance that can be modelled by AIRDIS.

3.0 SOURCE TERM CHARACTERISTICS

3.1 Radioactive and Stable Elements of Concern

The characteristics of Rabbit Lake tailings have been reported in terms of characteristics of the ore, major element analyses of tailings samples, and leachability studies on the tailings. These data are summarized in Table 3.1.1. The data of the first two columns have been also given in Chapter 2 respectively in Tables 2.3 and 2.4. The first column represents an average concentration of ten grab samples of ore assessed by Ruzeka (1986). The second column represents a summary of data from an Eldorado internal report (Eldorado, 1986), which made a preliminary evaluation of the leachability of uranium, radium-226 and Pb-210 from the Rabbit Lake mill tailings.

Inspection of the table indicates that uranium and its decay products are the only elements of major radiological or toxicological concern. The ore analyses (Column 1) suggest that there is little or no thorium present. However, the subsequent studies (Columns 2 and 4) indicate that thorium is present in the 10 to 30 ppm range. The lower end of the range is typical of the average concentration of thorium in soils globally (UNSCEAR, 1982).

To put the radionuclide levels associated with the Rabbit Lake tailings into an overall perspective, it is worthwhile to make a few comparisons with other media. The typical uranium content of 200 to 300 ppm in the tailings is considerably higher than that of typical soils (0.8 to 4 ppm) and construction granite (5 ppm) and only two to four times higher than that of phosphate fertilizers (40 to 170 ppm) applied to domestic gardens and agricultural lands. The Th-232 content of about 13 to 24 ppm in the tailings is higher than thorium contents of 2.5 to 12.5 ppm in global soils. In the past, thorium was incorporated into opthalmic glass at up to 30% by weight, although radioactivity in optical lenses has now been reduced (UNSCEAR, 1982). In the surface 1 m of typical soil containing 25 Bq/kg of uranium and its daughters and 28 Bq/kg (7 ug/g) of thorium and its daughters (UNSCEAR, 1982) over an area of 1 km², there is an equivalent amount of thorium in about 10 km² of soil and of uranium in about 700 km² of soil, as contained in the Rabbit Lake tailings.

TABLE 3.1.1: CONCENTRATION OF ELEMENTS IN RABBIT LAKE ORE AND TAILINGS

Element		Value ^a (1)	Value ^b (2)	Value ^c (3)	Value ^d (4)	Value ^e (5)	Value ^f (6)
Calcium (mg/g)	Bulk C F	GT 3.8	(44) 12 66	20	-	16	16,14,34
Barium (mg/g)	Bulk C F	0.17	-	0.264	0.23,0.19, 0.48	0.0051	0.013,0.008, 0.41
Lead (mg/g)	Bulk C F	3.2	-	-	-	-	1.6,1.5,2.4
Aluminum (mg/g)	Bulk C F	43	(51) 51 51	-	-	-	-
Iron (mg/g)	Bulk C F	38	(23) 24 22	-	20,18,24	-	-
Sulphate (mg/g)	Bulk C F	-	(105) 37 207	90	-	4.6	-
Thorium (ug/g)	Bulk C F	nf	(20) 13 24	-	23,16,22	-	-
Uranium (ug/g)	Bulk C F	34,400	(290) 270 310	-	215,226,223	-	-
Uranium (Bq/g)	Bulk C F	-	(3.5) 3.3 3.8	-	-	-	-
Th-230 (Bq/g)	Bulk C F	-	(31) 13 43	38.3	-	-	-

TABLE 3.1.1: CONCENTRATION OF ELEMENTS IN RABBIT LAKE ORE AND TAILINGS

Element		Value ^a (1)	Value ^b (2)	Value ^c (3)	Value ^d (4)	Value ^e (5)	Value ^f (6)
Ra-226 (Bq/g)	Bulk	-	(38.2)	38.3	-	-	-
	C	-	8.5		-	-	-
	F	-	58		-	-	-
Pb-210 (Bq/g)	Bulk	-	(32.2)	38.3	-	-	-
	C	-	12.5		-	-	-
	F	-	47		-	-	-
Po-210 (Bq/g)	Bulk	-	(44.6)	38.3	-	-	-
	C	-	12.5		-	-	-
	F	-	66		-	-	-

^a Ore sample (analysis on grab samples: Ruzicka, 198..).

^b Tailings: Eldorado Internal Report (PR-85-39). Quantity in brackets for bulk concentrations is calculated assuming 60% slimes and 40% coarse in tailings.

^c Mill Mass Balance.

^d Tailings: NAA (neutron activation analysis) of S2-1, S3-10 and S3-15 tailings.

^e Tailings: Distilled water washing experiment of tailings.

^f Tailings: Washing (extraction experiment - respectively 1:1 HCl; 1:1 HCl; 0.1 M EDTA pH = 9.5).

C = coarse tailings

F = fine tailings

nf = not found

The porewater of the Rabbit Lake tailings was sampled in November 1986 and analyzed for radiological elements and major ions. The analytical results are summarized in Table 3.1.2. They indicate the presence of U-238 decay series nuclides and Th-232. The major elements are calcium, sulphate, magnesium, bicarbonate and smaller quantities of sodium, potassium, aluminum and iron. Sulphate was derived from sulphuric acid used in the mill, and calcium from lime added to neutralize the tailings decant. Other elements were derived from the ore. Barium was derived from the ore and was added in the mill to coprecipitate radionuclides.

Evaluation of these data from an equilibrium point of view (see Appendix C) indicate that the water is close to saturation with respect to gypsum and calcite, but undersaturated with respect to magnesium sulphate. Other minerals assessed are indicated in Appendix C.

The porewater data indicate that U-238 decay series nuclides are the main radiological elements of concern. The porewater and solid phase data indicate that there are no apparent stable elements, such as arsenic, of chemical toxicological concern. Accordingly, the major elements which are considered in this study are those which are geochemical controllers upon the dissolution (leaching) of radionuclides from the tailings pile.

A listing of the aqueous substances considered in the code is given in Table 3.1.3. A listing of the solid forms considered is given in Table 3.1.4. These solid forms and the associated porewater species are similar to those considered previously in the Demonstration of UTAP (BEAK, 1986). Calcium, sulphate, carbonate and alkalinity are major geochemical controllers of solution pH. In addition, magnesium is considered because it dominated the chemical condition of electroneutrality conditions during milling operations. Barium (in barite, BaSO_4), lead (in anglesite, PbSO_4) and calcium (in gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) are geochemical controllers upon the dissolution of Ra-226 and daughters. Manganese, iron and aluminum influence pH and provide adsorption sites as the hydroxides. They can also coprecipitate radionuclides, but thermodynamic data for evaluating that role are not available and the kinetics are not clearly understood.

Th-232 has been considered previously for Elliot Lake ores due to its presence in uranium minerals such as brannerite, and in lanthium phosphate minerals such as monazite. It was

TABLE 3.1.2: OBSERVED VALUES FOR RABBIT LAKE POREWATER
(October 1986)

Element	Mean Value ± Std. Deviation	Number of of Samples (n)	Range of Values
Ra-226 (Bq/L)	3.13±1.35	n = 9	1.2-5.5
Th-232 (Bq/L)	0.106±0.036	n = 7	0.05-0.14
Th-230 (Bq/L)	1.57±0.71	n = 7	0.8-3.0
Pb-210 (Bq/L)	5.1±4.1	n = 7	1.3-13
Po-210 (Bq/L)	0.71±0.50	n = 7	0.14-1.4
U (ug/L)	3,460±2,450	n = 10	1,100-8,200
Ca (mg/L)	406±51	n = 10	385-505
Mg (mg/L)	1,300±310	n = 10	1,060-1,990
SO ₄ (mg/L)	7,000±1,660	n = 9	5,470-10,200
Ba (mg/L)	0.035±0.017	n = 10	0.017-0.067
Pb (mg/L)	LT 0.02	n = 10	-
Alkalinity (mg/L)	128±73	n = 4	77-234
pH	6.87±0.26	n = 4	6.56-7.18

TABLE 3.1.3: ROLE OF SUBSTANCE IN SOURCE TERM MODEL

Substance	Role of Substance
Calcium	Influences electroneutrality, pH
Sulphate	Influences electroneutrality, pH
C _T (total inorganic carbon)	Influences electroneutrality, pH
Magnesium	Significant porewater component at t = 0
Manganese	Adsorption sites; influences pH
Alkalinity	Influences pH
pH	Master chemical variable
Iron	Adsorption sites; influences pH
Aluminum	Adsorption sites; influences pH
Lead (Stable)	Influences Pb-210, Ra-226
Barium	Influences Ra-226 chemistry
Uranium	Radiological concern, chemical toxicity
Th-232	Geochemical control of Th-230
Th-230	Radiological concern
Ra-226	Radiological concern
Pb-210	Radiological concern
DOC	Influences redox
DO	Influences redox
Ammonia	Chemical toxicity at t = 0

TABLE 3.1.4: SOLID FORMS CONSIDERED

Name of Solid Form	Code Symbol for Solid Form	Units*	Code Name for Solubility Constant
Gypsum	CASO ₄ (I)	mol/m ³	XCASO ₄
Calcite	CACO ₃ (I)	mol/m ³	XCACO ₃
Iron Hydroxide	FE ₂ OH ₃ (I)	mol/m ³	XFE ₂ OH ₃
Thorium Hydroxide	THO ₂ (I)	mol/m ³	XTHO ₂
Aluminum Hydroxide	ALO ₂ OH ₃ (I)	mol/m ³	XALO ₂ OH ₃
Lead Sulphate	PBSO ₄ (I)	mol/m ³	XPBSO ₄
Lead Hydroxide	PBOH ₂ (I)	mol/m ³	XPBOH ₂
Lead Carbonate	PBCO ₃ (I)	mol/m ³	XPBCO ₃
Barium Sulphate	BASO ₄ (I)	mol/m ³	XBASO ₄
Particulate Organic Carbon**	POC(I)	mol/m ³	-
Th-230 Coprecipitate***	-	-	-
Ra-226 Coprecipitate***	-	-	-
Pb-210 Coprecipitate***	-	-	-

* Units: mol/m³ of bulk.

** Kinetic control of dissolution is assumed.

*** Calculated based upon distribution coefficients.

not considered in the previous UTAP demonstration for northern Saskatchewan tailings (BEAK, 1986) because of the perception that "the ores do not contain any thorium of significance". But, for Rabbit Lake, the Neutron Activation Analyses (NAA, Column 4, Table 3.1.1) indicate that thorium levels are somewhat higher than global soils, and the porewater analyses indicate that Th-232 activity is close to saturation with thorium hydroxide (see Appendix C and Table 3.1.5). Accordingly, Th-232 solubility is considered in this study.

To determine the abundance of elements in the different secondary precipitate phases of the tailings upon decommissioning, four data sources, in addition to that of Eldorado (1986; see Column 2, Table 3.1.1), are available to aid in determining their composition. Mill data (Column 3, Table 3.1.1) are based upon the addition of chemicals added to the mill (see Table 3.1.6). Neutron activation analyses (Column 4, Table 3.1.1) were made upon three samples obtained from Geocon boreholes drilled as part of the NUTP program (S-2-1 is Core S2 at depth 1 m; S3-10 and S3-15 are from Cores S3 at 10 and 15 m of depth). Washing experiments using 50 batch leaches (1:10 ratio) were made upon S3-10; the results given in Table 3.1.1 (Column 5) are the total mass washed off. Similarly, mass values given in Column 6 of Table 3.1.1 are the masses washed off using HCl solutions (first two values) and an EDTA solution (third value).

Based upon an analyses of these data, the mass values chosen for this project and the associated thermodynamic data are given in Table 3.1.7. The calcium and sulphate values are the average of the Eldorado report and the EDTA wash. This is consistent with the mill addition of sulphuric acid. The mill addition number for calcium is rejected as being too low because it is only 50% of the mass of sulphuric acid added; it is assumed that the additional amount of calcium is derived from the ore. For barium, the average of the neutron activation and the EDTA wash is used.

Two other points are in order for this data compiled in Table 3.1.7: the initial values used for coarse and fine tailings and the thorium hydroxide solubility constant. The analytical data of Eldorado (1986, internal report) given in Table 3.1.1 indicate that U-238, Th-232, Ra-226, Pb-210, Po-210, Th-232, sulphate and calcium have a particle-size-dependent concentration. However, the data for magnesium, sodium, potassium, iron and aluminum are independent of the particle size distribution. These particle size effects are consistent with the former elements being present mainly as secondary precipitates

TABLE 3.1.5: SOLUBILITY CONSTANT FOR THORIUM PHASE

Phase	Phase Name	Reaction Form	Solubility Constant	Reference
am-Th(OH) ₄ (s)	Amorphous thorium hydroxide	-	?	-
Th(OH) ₄ (s)	not specifically given	Reaction 1 Reaction 2	log K = 9.4 log K = -46.6	Langmuir and Herman (1980) quoting Baes and Mesmer
-	Amorphous thorium hydroxide	Reaction 1	log K = 6.3	SENES (1985)
ThO ₂ (act)	Active oxide	Reaction 3 Reaction 1	log K = -6.32 log K = 9.58	Baes and Mesmer (1976)
ThO ₂ (c)	Name not specifically given	Reaction 1 Reaction 2	log K = 6.3 log K = -49.7	Langmuir and Herman (1980) quoting Baes and Mesmer
ThO ₂ (c)	Well crystallized oxide	Reaction 3 Equation Rxn 1	log K = -9.6 log K = 6.3	Baes and Mesmer (1976)
ThO ₂ (th)	Thorianite	Reaction 1 Reaction 2	log K = 1.8 log K = -54.2	Langmuir and Herman (1980)
ThO ₂	Completely insoluble (crystalline) thorium	Reaction 1	log K = 1.78	SENES (1985)

Notes:

1. Reaction 1: $\text{ThO}_2(\text{s}) + 4\text{H}^+ = \text{Th}^{4+} + 2\text{H}_2\text{O}$
 Reaction 2: $\text{ThO}_2(\text{s}) + 2\text{H}_2\text{O} = \text{Th}^{4+} + 4\text{OH}^-$
 Reaction 3: $\text{ThO}_2(\text{s}) + 2\text{H}_2\text{O} = \text{Th}(\text{OH})_4(\text{aq})$

2. Solubility Product Relationships:

$$\begin{aligned} \text{Rxn 1 (logK)} &= \text{Rxn 2 (logK)} - 56 \\ \text{Rxn 3 (logK)} &= \text{Rxn 1 (logK)} - 15.9 \end{aligned}$$

TABLE 3.1.6: ADDITION OF CHEMICALS IN MILL (1979-1985)

Substance	Value (kg/tonne)		Average (mg/g)
	Range	Average	
Ammonia	3.6-4.8	3.9	-
Sulphuric Acid	162-271	185	90 as sulphate
Lime (CaO)	47-70	55	20 as Ca
Barium Chloride	0.71-0.98	0.8	0.264 as Ba
Ammonium Sulphate	0.05-0.09	0.06	-
Soda Ash (NaO)	0.21-0.5	0.3	-
Calgon	0.01-0.04	0.02	-
Sodium Chlorate	3.8-5.7	5.2	-

TABLE 3.1.7: SOURCE TERM MODEL VARIABLES

Symbol	Description	Units	Nominal Value	Probabilistic	Source	Computer Symbol
A	Area of Tailings Site	m ²	5E+5	5E+5	INPUT	ATAIL
R	Rainfall Rate	m'a ⁻¹	0.4	0.4	INPUT	RAIN
I	Infiltration Rate	m'a ⁻¹	-	N (0.23, 0.09, 0.14, 0.47)	INPUT	INFT
Zi	Thickness of Box	m	for I = (1,2,3,4), Z = (0.1,1.9,4.0,10.0)		INPUT	ZTAIL(I)
n	Porosity in Box	-	0.5	0.5	INPUT	POR(I)
p	Dry Bulk Density	g cm ⁻³	1.2	1.2	INPUT	RHOT(I)
g _{po}	Percent of void space which is gas	-	for I = (1,2), g _{pc} = u (0.1,0.5) for I = (3,4), g _{pc} = 0		INPUT	GASPC(I)
Q _d	Downflow rate between boxes	m ³ a ⁻¹	for I = (1,2,3,4,5) QD(I) = (1.0,1.0,1.0,0.05,0.001)		INPUT	QDPC(I)
Q _u	Upflow rate between boxes	m ³ a ⁻¹	0	0	INPUT	QUT(I)
-	Probabilistic coefficient for varying QUT	-	1.0	1.0	INPUT	QUDIST
Q _i	Inflow rate from upstream	m ³ a ⁻¹	1.0	1.0	INPUT	QINT(I)
Q _u dist	Probabilistic coefficient for varying QINT	-	1.0	1.0	INPUT	QINDIST
Q _o	Outflow rate from boxes	m ³ a ⁻¹	-	-	Calculated	QO(I)
Ex	Exchange rate between boxes (diffusional processes)	m ³ a ⁻¹	0	0	INPUT	EXCHT(I)
Ex _{dist}	Probabilistic coefficient for varying exchange	-	1.0	1.0	INPUT	EXDIST
Ca(SO ₄)	Concentration of gypsum in coarse tailings	mol g ⁻¹	2.65E-04 (initial)	T(2.30E-04,2.65E-04, 3.0E-04)	Calculated	CASO4TC
	Concentration of gypsum in fine tailings	mol g ⁻¹	1.45E-04 (initial)	T(1.26E-03,1.45E-03, 1.64E-03)	Calculated	CASO4TF
CaCO ₃	Concentration of calcite in tailings solids	mol g ⁻¹	5.0E-04 (initial)	T(4.0E-04,5.0E-04, 6.0E-04)	Calculated	CACO3T
UO ₂	Concentration of uranium oxide in tailings solids	mol g ⁻¹	9.4E-07 (initial)	T(8.4E-07,9.4E-07, 1.14E-06)	Calculated	UO2TC
	Concentration of uranium oxide in fine tailings	mol g ⁻¹	1.08E-06 (initial)	T(9.7E-07,1.08E-06, 1.3E-06)	Calculated	UO2CF
FeOOH	Concentration of goethite in tailings solids	mol g ⁻¹	1.125E-04 (initial)	T(1.00E-04,1.125E-04, 1.235E-04)	Calculated	FeOOH
Al(OH) ₃ (s)	Concentration of gibbsite in tailings solids	mol g ⁻¹	1.28E-04 (initial)	T(1.15E-04,1.28E-04, 1.41E-04)	Calculated	ALOH3T
PbSO ₄	Concentration of lead sulphate in tailings solids	mol g ⁻¹	1.35E-06 (initial)	T(1.16E-06,1.35E-06, 1.54E-06)	Calculated	PBSO4T
BaSO ₄	Concentration of barite in coarse tailings	mol g ⁻¹	1.5E-06 (initial)	T(1.2E-06,1.5E-06, 1.7E-06)	Calculated	BASO4TC
	Concentration of barite in fine tailings	mol g ⁻¹	3.2E-06 (initial)	T(2.6E-06,3.2E-06, 3.5E-06)	Calculated	BASO4TF
Th(OH) ₄ (s)	Thorium hydroxide in coarse fraction of tailings	mol g ⁻¹	5.6E-08	T(4.5E-08,5.6E-08, 6.2E-08)	Calculated	THOH4TC
	Thorium hydroxide in fine tailings	mol g ⁻¹	1.03E-07	T(0.8E-07,1.03E-07, 1.1E-07)	Calculated	THOH4TF
Th-230	Th-230 in coarse tailings	Bq'g ⁻¹	12.1	T(9.7,12.1,14.5)	Calculated	TH230C
	Th-230 in fine tailings	Bq'g ⁻¹	55.7	T(45,55.7,67)	Calculated	TH230F
Ra-226	Radium-226 in coarse tailings	Bq'g ⁻¹	12.1	T(9.7,12.1,14.5)	Calculated	RA226TC
	Radium-226 in fine tailings	Bq'g ⁻¹	55.7	T(45,55.7,67)	Calculated	RA226TF

TABLE 3.1.7: SOURCE TERM MODEL VARIABLES

Symbol	Description	Units	Nominal Value	Probabilistic	Computer Source	Symbol
Pb-210	Pb-210 in coarse tailings	Bq·g ⁻¹	12.1	T(9.7,12.1,14.5)	Calculated	PB210TC
	Pb-210 in fine tailings	Bq·g ⁻¹	55.7	T(45,55.7,67)	Calculated	PB210TF
K-Pb(OH) ₂	Solubility product for lead hydroxide	Lmol ⁻¹	LN (0.0E0, 1.59, -)		INPUT	XPBOH2
K-PbCO ₃	Solubility product for lead carbonate	Lmol ⁻¹	LN (7.943E-14, 1.59, 1.995E-14, 3.162E-13)		INPUT	XPBCO3
K-BaSO ₄	Solubility product for barium sulphate	Lmol ⁻¹	LN (1.00E-10, 1.59, 2.512E-11, 3.918E-10)		INPUT	XBASO4
I	Ionic strength	mol·L ⁻¹		Calculated	SOURCE	XIOS
C _{topj}	Rainfall concentrations	mol·L ⁻¹	Ca=2.0E-5 SO ₄ =1.0E-5 CT=1.0E-5	-	INPUT	CTOP(J)
C _{inj}	Inflow concentration to boxes from upstream	mol·L ⁻¹	all set at zero	-	INPUT	CINT(J)
C _{deepj}	Concentration going to groundwater	mol·L ⁻¹	Calculated	-	SOURCE	CDEEP(J)
S _j	Sorbing surface concentration	m ² ·g ⁻¹ mol·L ⁻¹ or sites L ⁻¹	Dependent on element		INPUT	SURF(J)
K _{dj}	Sorption constant	L·kg ⁻¹	Dependent on element			KDT(J)
C _{i,j}	Concentration in pore water of component i in box j	mol·L ⁻¹	-	-	Calculated	C(I,J)
C _{T i,j}	Total dissolved concentration of component i in box j	mol·L ⁻¹	-	-	Calculated	CT(I,J)
C _{ads i,j}	Concentration of adsorbed component i in box j	mol·L ⁻¹	-	-	Calculated	CADS(I,J)
C _{TT i,j}	Total dissolved concentration of component i in box j	mol·L ⁻¹	-	-	Calculated	CTT(I,J)
C _{TOT i,j}	Total dissolved, adsorbed and solid concentration of component i in box j	mol·L ⁻¹	-	-	Calculated	CTOT(I,J)
D _{Ra-Ca}	Distribution coefficient for Ra in gypsum	-	T (20, 50, 75)	-	INPUT	DRACA
D _{Ra-Pb}	Distribution coefficient for Ra in lead sulphate	-	T (0.417, 0.687, 1.25)	-	INPUT	DRAPB
D _{Ra-Ba}	Distribution coefficient for Ra in barium sulphate	-	T (0.086, 0.112, 0.137)	-	INPUT	DRABA
D _{Th-Fe}	Distribution coefficient for Th in iron hydroxide	-	T (0.5, 1.0, 1.5)	-	INPUT	DTHFE
D _{Th-Mn}	Distribution coefficient for Th in manganese oxide	-	T (0.5, 1.0, 1.5)	-	INPUT	DTHMN
K _{s-gypsum}	Solubility constant for gypsum	mol ² ·L ⁻²	LN (2.399E-5, 1.05, 2.138E-5, 2.75E-5)		INPUT	XCASO4
K _{s-calcite}	Solubility constant for calcite	mol·L ⁻¹	LN (4.467E-9, 1.05, 3.891E-9, 5.128E-9)		INPUT	XCACO3
K _{s-goethite}	Solubility constant for goethite	L ² ·mol ⁻²	LN (3.98E+1, 3.16, 1.259E0, 1.259E+3)		INPUT	XFE00H
K _{s-gibbsite}	Solubility constant for gibbsite	L ² ·mol ⁻²	LN (2.399E+10, 3.16, 7.587E+8, 7.586E+11)		INPUT	XALOH3
K _{s-PbSO₄}	Solubility constant for lead sulphate	mol ² ·L ⁻²	LN (1.585E-8, 1.59, 3.98E-9, 6.31E-8)		INPUT	XPBSO4
Decay	Decay rate of particulate material	a ⁻¹	10 ⁻³ for all values		FIXED	DECAY(I,J)
Radiod	Radionuclide decay rate	a ⁻¹	(J=2,3,4) = 8.664E-6; 4.273E-3; 3.397E-3		FIXED	RADIOD(J)
f	Activity coefficient	-	-		Calculated	F(I,J)

TABLE 3.1.7: SOURCE TERM MODEL VARIABLES

Symbol	Description	Units	Nominal Value	Probabilistic	Source	Computer Symbol
$K_s\text{-ThO}_2$	Solubility constant for thorium hydroxide	8.7E+07	LN(8.7E+07, 3.16, 2.0E+6, 3.8E+9)			
THU	Th-U constant in urananite	Bq·g ⁻¹	1.656E-3	-	FIXED	THU
RAU	Ra-U constant in urananite	Bq·g ⁻¹	3.191E-7	-	FIXED	RAU
RATH	Ra-Th mass activity constant	-	49.32	-	FIXED	RATH
PB210U	Pb210-U constant in urananite	Bq·g ⁻¹	3.618E-9	-	FIXED	PB210U
PBRA	Pb-Ra mass activity constant	-	74.3	-	FIXED	PBRA

which form in the mill, and the latter elements being present in primary minerals originally found in the ore and unleached in the mill. The particle size effect is due to small particles having a larger surface area per gm of solids than larger particles. If the secondary precipitates form as small precipitates (e.g., 1 to 10 μ m) on the surface of the larger primary minerals, with the same surface density on all sizes of primary minerals, they will be concentrated in the fine fraction. Formation of small secondary precipitates (1 to 10 μ m) as particles separate from the primary minerals also increases their concentration in the fines fraction in addition to the surface area effect.

For this study, the former list, except for U-238, is taken to be present as secondary precipitates, while the latter list is taken to be primarily present in the host matrix of primary minerals. U-238 is taken to be not size-dependent because the particle size effect is small compared to that of other secondary precipitates, and because U-238 should be present previously in residual minerals. Elements such as iron and aluminum must have a small particle size effect because iron and aluminum are present in the leaching liquor; however, the amount of these elements as secondary precipitates must be too small to show a particle size effect.

The "bulk" data given in Table 3.1.1 for the radionuclides is calculated assuming that the complete Rabbit Lake tailings mass is 60% slimes and 40% coarse. This is based upon the analysis of (Eldorado, 1986). The bulk values of 31 Bq/g, 38.2 Bq/g, 33.2 Bq/g and 44.6 Bq/g for Th-230, Ra-226, Pb-210 and Po-210, respectively, average 36.8 Bq/g, while the overall ore grade for uranium of 0.31% U is equivalent to 38.3 Bq/g. Accordingly, it is concluded that these activity measurements are consistent with the ore grade, and that these radionuclides are present at levels which represent secular equilibrium with the ore grade. The ore grade is used to estimate the initial concentrations given in Table 3.1.7.

For thorium hydroxide, the solubility constants, summarized in Table 3.1.5, indicate that there are over eight orders of magnitude range dependent upon the solid phase present. The porewater data were used to infer a solubility constant for the Rabbit Lake tailings. The value ($\log K_s = -7.9$) suggests that the thorium hydroxide solid phase emulates that of the well-crystallized oxide described by Baes and Mesmer (1976). For modelling purposes, a somewhat larger range is given to the frequency distribution for the thorium hydroxide solubility constant than that for other solid phases (see Table 3.1.7), because of the uncertainty associated with the phase, and because the calculation from the observed

porewater assumes equilibrium conditions, whereas the system may be near to, but not at, equilibrium.

3.2 Hydrology of Tailings

Three studies are available which aid in establishing the hydrology of the tailings. A tailings seepage study (Geocon, 1982) involved installation of piezometers and sampling at locations around the site. As well, groundwater modelling was undertaken to define flow pathways through the tailings.

A second study, funded by the National Uranium Tailings Program, involved coring the tailings and estimating permeability values in the tailings pile (Geocon, 1986).

A third study (BEAK, 1987), funded by Eldorado in support of this study, involved finite element modelling of the tailings and local groundwater to estimate hydrology of the tailings after decommissioning.

The results of the three studies are summarized in Figure 3.2.1. During operation, most of the tailings were discharged from the North Dam. The tailings deposited near the discharge were mainly coarse. Fines were transported to strata associated with Boxes 3 and 4. During the initial years of operation, cycloned (coarse) tailings were deposited near the south dam while, in the latter years, tailings discharge from the south dam resulted in coarse tailings settling out near the dam. This has resulted in the top of the south zone and the zone adjoining the north dam being coarse with intermediate zones being composed of fines.

For final design, Eldorado has proposed that the surface, including the frozen area, be covered with coarse tailings to a depth of 3 m. For modelling purposes, a seven-box modelling structure was adopted. Boxes 1, 2 and 6 are coarse tailings which constitute the tailings having voids partially or wholly filled by gas. These boxes exist presently, or result from the reshaping of the surface. Boxes 1 and 2 also cover the frozen zone. Boxes 5 and 7 are coarse, while Boxes 3 and 4 are fines.

To define water flow pathways, the Geocon (1982) study, amplified by the flow modelling of this study and water balances by Eldorado (Filion, pers. comm.), were used. The

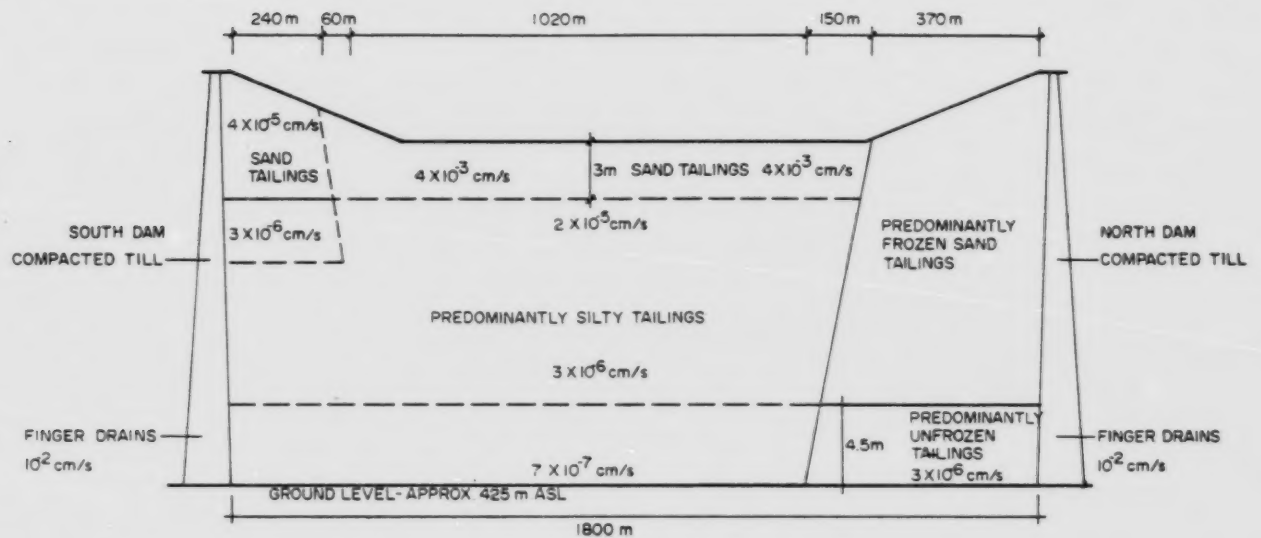


FIGURE 3.2.1a Schematic of Tailings After Consolidation and Before Covering Through A-A (Assumes 4m Consolidation in Slimes Area)

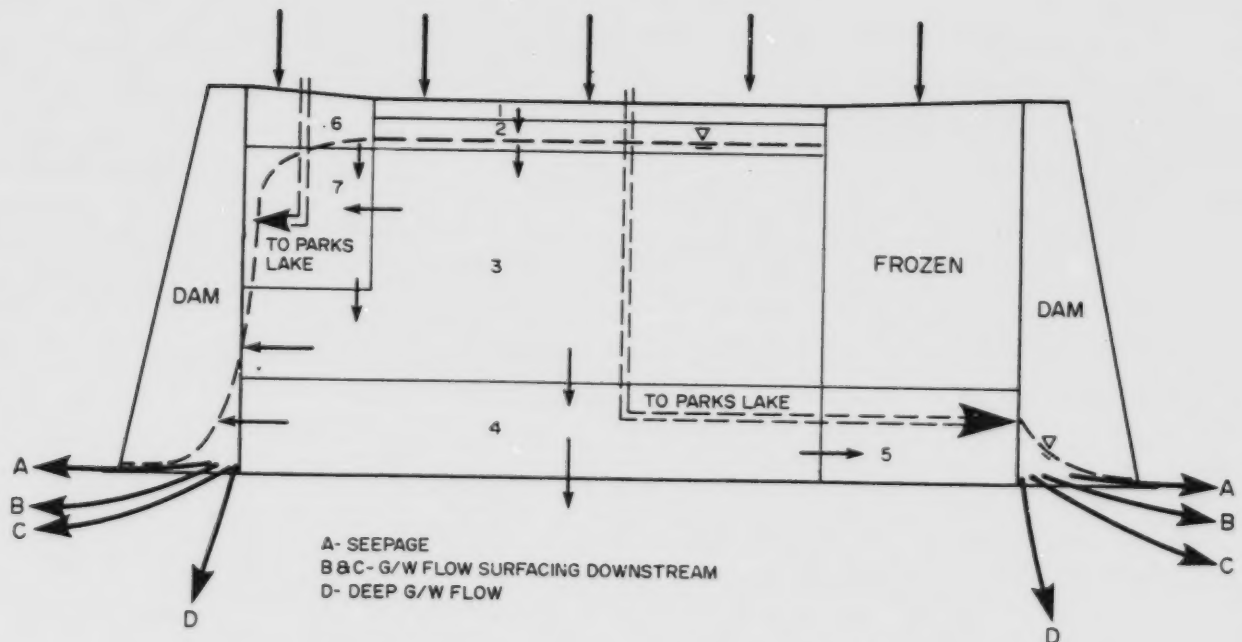


FIGURE 3.2.1b

Schematic Cross-Section Through the Center of the Tailings Ponds Demonstrating Major Flow Pathways

Geocon study suggests that there were two major modes of infiltration to the tailings, and three major modes of exfiltration from the tailings. There is a pathway which involves flow from the west ridge through the tailings and east ridge to Parks Lake. This is shown in Figure 3.2.1b as the dotted arrow. Infiltration of rainfall also occurs through the tailings surface. Exfiltration occurs through the toe of the north and south dam.

The Geocon study also suggested that flow through each dam could be conceptualized as occurring along four pathways (see Figure 4.2). The pathways flow through the ground and come to the surface respectively at the toe of the dam, 200 m and 800 m from the toe of the dam and several kilometres from the dam. For this study, the three surficial pathways are used for modelling seepage from the tailings (see Figure 4.2, Chapter 4).

The boxes and flow pathways adopted for this study are given in Figure 3.2.1b. Net infiltration (infiltrating rainfall) occurs from Boxes 1 to 2 and then from 2 to 3, and from Boxes 6 to 7. Water flow occurs from Box 3 to Box 7 and from Box 3 to Box 4. Flow leaves the tailings from Boxes 7, 3 and 4 through the south dam and from Box 5 through the North Dam. Flow also occurs into and from Boxes 3, 4, 5 and 7 to reflect flow from the West Ridge through the saturated zone of the tailings and then through the East Ridge to Parks Lake.

In the code, provision is also made for lateral flow from Boxes 1, 2, 3 north, and Boxes 1, 2, 6 and 7 south. These flow rates are set to zero because of the frozen zone or because the zones in question are unsaturated, implying that flow occurs only vertically downward. They are included in the code in case a possible future management option involves fully saturated tailings, and for calibration studies under present conditions where a pond occurs.

Several water balance estimates have been made. The definitive estimate was made by Eldorado (Filic, pers. comm.) for 1981 operating conditions and for the long-term operating conditions. The results are given in Table 3.2.1. The terms QPREC, QGIW and QTI are the inputs to the tailings from net precipitation, the west ridge, and to the tailings (see Figure 3.2.1). The terms QGONA and QGOSA are groundwater flow from the north and south dam for the four groundwater pathways. QGOE and QBO are outflow to the east ridge and the barge. QEVAP and QACCUM are evaporation and accumulation in the tailings. Each water flow was estimated, semi-independently of the other. Inflows

TABLE 3.2.1: HYDROLOGIC BALANCES FOR TAILINGS MANAGEMENT SYSTEM FOR VARIOUS SITUATIONS (m³/a)

		During Operations 1981		After Decommissioning					
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6		
Inflows	QPREC QTI QGIW	3.59E+05 2.25E+06 1.13E+05	QGRUN QGIW	7.3E+04 3.0E+05	4.4E+04 N/A 3.1E+05	2.2E+04 N/A 3.2E+05	7.8E+04 N/A 3.0E+05	0.0E+00 N/A 3.2E+05	1.5E+05 N/A 2.7E+05
Outflow North	QGONA QGONB QGONC QGOND	-5.07E+04 -4.50E+04 -3.61E+04 -5.29E+04	QGONA QGONB QGONC QGOND	-1.8E+04 -1.6E+04 -1.4E+04 -2.6E+04	-1.6E+04 -1.4E+04 -1.3E+04 -2.4E+04	-1.5E+04 -1.3E+04 -1.2E+04 -2.3E+04	-1.8E+04 -1.6E+04 -1.4E+04 -2.6E+04	-1.3E+04 -1.2E+04 -1.1E+04 -2.1E+04	-2.3E+04 -2.0E+04 -1.7E+04 -3.0E+04
Outflow South	QGOSA QGOSB QGOSC QGOSD	-8.62E+04 -7.64E+04 -6.14E+04 -8.98E+04	QGOSA QGOSB QGOSC QGOSD	-4.0E+04 -3.5E+04 -3.7E+04 -5.8E+04	-3.7E+04 -3.3E+04 -3.5E+04 -5.6E+04	-3.5E+04 -3.1E+04 -3.4E+04 -5.4E+04	-4.0E+04 -3.5E+04 3.7E+04 -5.8E+04	-3.3E+04 -2.9E+04 -3.3E+04 -5.3E+04	-4.7E+04 -4.1E+04 -4.0E+04 -6.2E+04
Outflow East Decant	QGOE QBO	-1.72E+05 -1.35E+06	QGOE	-1.3E+05 N/A	-1.2E+05 N/A	-1.2E+05 N/A	-1.3E+05 N/A	-1.2E+05 N/A	-1.3E+05 N/A
Evaporation	QEVAP	-2.12E+05		N/A	N/A	N/A	N/A	N/A	N/A
Accumulation	QACCUM	-4.71E+05		N/A	N/A	N/A	N/A	N/A	N/A
Inflow-Outflow		1.54E+04		-6.7E-10	-1.8E-11	4.7E-10	-6.8E-10	9.2E-10	1.0E-09
Equilibrium Water Table (ET, ASL)				432.1	431.5	431.1	432.1	430.6	433.6

- Case 1: Contoured surface, no cover
Case 2: Contoured surface, 0.6 m till, 0.15 m topsoil, vegetation
Case 3: Contoured surface, 0.5 m till, bentonite, 0.15 m topsoil, vegetation
Case 4: Contoured surface, 0.6 m waste rock
Case 5: No infiltration
Case 6: 100% infiltration

(QTI) and the barge are measured values. The remainder of the values are estimates or derived from the Geocon modelling study. This results in some of the estimates being only semi-independent because of the relationships between boundary conditions and calculated flows. The net water balance (difference between inflow and outflow) is small showing that these estimates are approximately correct.

The long-term estimates were made by evaluating steady-state piezometric conditions and using a head-loss, flow relationship which was calibrated from observations in monitoring wells between 1981 and 1983. The calculated head loss values result in significantly lower long-term head values than anticipated in the tailings (i.e., these calculations suggest that the unsaturated zone is in excess of 10 m of depth).

These calculated long-term conditions were evaluated in this study using a finite-element model (see Appendix B and BEAK, 1987). Most efforts centred upon evaluating 1981 conditions. The results indicate:

- o for the measured permeabilities (Geocon, 1986), the hydrological flow (estimated by Geocon, 1986) into the tailings is too large;
- o for the water balance during operating conditions (Table 3.2.1), the permeability of the tailings must be larger; and
- o using measured permeabilities and the long-term flow balance, the depth of the unsaturated zone is in excess of 10 m, consistent with the simple hydraulic flow - head calculations.

These inconsistencies occur because there must be a very hydrologically active area near the surface of the tailings, through which most of the flow occurred during operation of the tailings. Upon decommissioning, the main groundwater flow pathway must be lower in the tailings when the overall effective permeability is lower than that of the surficial few metres. Accordingly, a plausible case for actual permeabilities and the long-term flows of Table 3.2.1 was estimated and tested in a sensitivity run (see Appendix B and BEAK, 1987). These flow rates and an assumed unsaturated zone which corresponds to the coarse tailings cover of 3 m are used for the long-term modelling. To test the case that the unsaturated zone is 10 m thick, a sensitivity analysis is carried out and presented in Chapter 5.

3.3 Source Model

The source model for this probabilistic assessment was adapted from the source model developed previously for demonstration of UTAP on the non-pyritic tailings typical of northern Saskatchewan (BEAK, 1986). The same model equations were used for the saturated and non-saturated boxes. The major differences were the requirement to modify the code to handle seven boxes rather than four, allow for the horizontal flow in the north and south direction and across the tailings, and provision for boxes containing coarse or fine tailings. Consideration of this particle size distribution essentially results in different initial concentrations of minerals such as gypsum and the radionuclides for the fines and coarse fraction. As well, different interfacing subroutines were written to collect flow from the different boxes and to partition it to the groundwater pathways (see Section 4.2).

The associated input data for initial masses of minerals and radionuclides, thermodynamic constants and other constants are given in Table 3.1.7. The initial mass data, etc. have been explained above. Other data, such as frequency distributions for thermodynamic constants, are given in BEAK (1986).

3.4 Scenarios for Management of Tailings

The following management scenarios (See Section 2.6) have been adopted for evaluation in this study:

<u>Scenario</u>	<u>Description</u>
1	Base Case - no cover except natural
2	0.6 m sand overlain by 0.15 m top soil and vegetated
3	0.6 m soil and bentonite overlain by 0.15 m top soil and vegetated
4	0.6 m waste rock cover

Models are required to describe the effect of cover upon the water balance of the tailings (hence, the amount of rainfall which infiltrates, and the depth of the unsaturated zone), wind and water erosion, and radon exhalation. As well, a cover will change the rate of weathering of coarse tailings on the surface of the tailings due to freeze-thaw effects.

With respect to the water balance, most of the flow through the tailings is derived from groundwater flow rather than direct infiltration. However, the finite element modelling (see Appendix B and BEAK, 1987) indicates that the depth of the unsaturated zone is sensitive to the amount of infiltration. Net infiltration is taken to be 75% of that of the base case for Scenario 2 due to evapotranspiration, 10% of the base case for Scenario 3, and 150% of the base case for Scenario 4 due to the effect of rock in trapping water and allowing an increase in infiltration. The amount of infiltration in Scenario 4 would decrease over time due to evapotranspiration as the surface vegetates naturally. For this study, infiltration is assumed to be constant for the simulation period.

The depth of the unsaturated zone is assumed to be 3.75 m in the case of Scenarios 2 and 3, and 3.0 m in the case of Scenario 4. This makes the thickness of the top tailings box the same for Scenarios 2, 3 and 4 as for Scenario 1. It is assumed that the rock cover is sufficiently porous that it does not influence the rate of infiltration of rain water into the tailings. The moisture content of the unsaturated zone is assumed to be changed in the same manner as the amount of infiltration.

With respect to wind and water erosion, it is assumed that the covers effectively limit erosion to be zero from the time that the tailings are decommissioned.

Radon exhalation will be decreased by the cover by providing time for radon to decay before it diffuses to the atmosphere. A mathematical solution of the diffusion equation gives the equation:

$$\text{FLUX} = \text{RFLUXO} \cdot \exp(-A \cdot \text{ZCOVER}) \quad (1)$$

where A is equal to $(k/D)^{0.5}$. Here, k is the radon decay coefficient ($2.1 \times 10^{-6} \text{ s}^{-1}$), D is the gaseous diffusion coefficient (m^2/s), ZCOVER is the thickness of the cover, FLUX is the flux at the top of the cover, and RFLUXO is the flux from the tailings (at the bottom of the cover).

The effective diffusion coefficient (D_e) in the unsaturated zone can be estimated (Reardon and Modelle, 1984) from the equation:

$$D_e = \frac{52.56 (n_a - 0.05)^{1.7}}{0.95} \quad (2)$$

where n_a is the air-filled porosity, and D_e has units of $m^2 \text{ month}^{-1}$. This relation was experimentally derived for tailings typical of the Elliot Lake area. It is used to provide estimates of D_e for the covers. Values of 0.2, 0.15 and 0.4 are assigned to n_a respectively for Scenarios 2, 3 and 4.

The cover will also affect the chemistry of infiltrating water. The chemistry of rainfall will change to that of water passing through growing and decaying vegetation. The main effects will be:

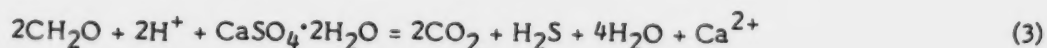
- o to buffer the pH at 6.5 to 7.0;
- o to increase the aluminum, silica, potassium and iron content;
- o to reduce the sulphate content; and
- o to increase the DOC (dissolved organic carbon) content of the infiltrating rainwater.

Changes in the content of the infiltrating rainwater will alter the geochemical mechanisms controlling radionuclide dissolution in the tailings porewater. The main effects will be upon thorium hydroxide solubility and DOC induced dissolution of sulphate minerals containing radionuclides. Thorium solubility will be largely unaffected by vegetation because its solubility is largely independent of pH over the range which vegetation will alter the pH. The DOC content could increase the thorium content slightly if thorium complexes with organic carbon, and decrease the content due to chemical precipitation of a thorium-organic matter solid. Information is inadequate to characterize the effect of DOC upon thorium solubility. Accordingly, it is assumed that vegetation will have a minimal effect upon thorium solubility.

DOC-induced dissolution of sulphate results from sulphate-reduction and bacterial reactions. Organic carbon, which enters the tailings with infiltrating rainfall, is derived from decaying vegetation on the surface. It is also present in the porewater as in a waste from the IX circuit (i.e., kerosene). DOC is an energy source for bacterial growth and synthesis, and sulphate is a final electron acceptor. DOC decay results in conversion

of dissolved sulphate into reduced forms such as sulphide. If all sulphate is depleted in the porewater, and if all sulphate-containing minerals are dissolved, then Ra-226 and Pb-210 will dissolve in substantial quantities. Sulphate reduction necessitates development of a kinetic redox model. Part of this model has been implemented in the code, but its application cannot be made, with confidence, due to two factors. The biogradability of organic carbon changes with time and influences the kinetics of carbon transformation. A model for predicting the changes in biodegradability is required, but not available. Secondly, the final geochemical form of reduced sulphate is not completely clear. Reduced sulphate will mainly be sulphide which can precipitate with metal ions (e.g., iron sulphide, manganese sulphide), but some intermediate forms are also possible, including organo-sulphide forms.

The potential role of organic carbon in the releasing radionuclides can be checked using mass balance calculations. Inspection of the data of Huck *et al.* (1986) on radium-barium sludges is one approach. A similar but simpler approach is to use a stoichiometric model and mass balance calculations as tools for estimating the potential amount of sulphate (and radium) which could be released. An appropriate stoichiometric model is:



This model states that 2 mol of carbon are required to dissolve and reduce 1 mol of gypsum to sulphide. Assuming that 20 mg/L of carbon leach from vegetation with infiltrating rainfall (0.10 m/a), sulphate in gypsum would be dissolved at the rate of 0.083 mol sulphate/m²/year due to redox processes. For a gypsum content on the Rabbit Lake tailings solids of 1 mol/g (see Table 3.1.1), there are approximately 10⁶ mol sulphate per m² in a 1 m strata of tailings. Accordingly, redox reactions would dissolve by sulphate reduction all the gypsum in 0.1 mm of tailings over a 1,000 year timeframe. This is insignificant.

Another way of examining the importance of redox reactions is to compare the impact of carbon-induced sulphate reduction to gypsum dissolution due to the flux of water through the tailings. Water containing 20 mg/L of carbon will dissolve the equivalent of 8.33x10⁻⁴ mol SO₄/L, while water saturated with respect to gypsum will dissolve 1.6x10⁻² mol SO₄/L. Furthermore, infiltrating rainwater is a small component of the total amount of water infiltrating the tailings. Accordingly, the DOC content of the

infiltrating rainwater must be approximately 400 mg/L for redox reactions to have an equivalent impact as infiltrating rainwater. Upon removal of sulphate from the tailings solids, such concentrations are unlikely. There are substantial quantities of kerosene currently present. However, once it is flushed out, there will not be a sustained source of DOC. It is concluded that redox reactions will have a minimal impact upon release of radionuclides from the tailings relative to other mechanisms affecting release, and they are not included in the model.

3.5 Calibration of Source Term

A comparison between model predictions and observations is presented in Figures 3.4.1 to 3.4.11 for calcium, sulphate, magnesium, total carbonate, pH, barium, lead, uranium, Th-232, Ra-226 and Pb-210 for the period 1976-1985. Parameter values and their distributions used for the simulation presented in Figures 3.4.1 to 3.4.11 are given in Table 3.1.7. The parameter values are generally the same as those used previously, except for the critical concentrations and the adsorption coefficients and distribution (coprecipitation) values for Ra-226 and Pb-210. The results indicate that the calculated values for the major elements are in reasonable agreement. As noted in the appendix, calcium activity is not equal to sulphate activity because magnesium complexes a large portion of the sulphate. However, over the long-term, magnesium contained in the porewater is flushed out and the calculated activity of calcium and sulphate come into rough balance.

The radionuclide activity of Ra-226 and Pb-210 shows reasonable agreement between observed values and calculated values. This agreement was obtained by decreasing the coprecipitation distribution coefficients for Ra-226 in gypsum, barite and anglesite by a factor of 16 and distribution coefficient of Pb-210 in barite by 10. The changes are necessary to obtain an agreement between model predictions and observations. The original values for Ra-226 coefficient used in BEAK (1986) were those of Langmuir and Reise (1984). These values were developed for precipitation experiments in the laboratory. There is theoretically no reason why the distribution coefficient derived from precipitating solutions should be the same as those in dissolution solutions, unless the theory is derived for both conditions. In this work, it is assumed that field conditions are dissolving conditions.

FIGURE 3.4.1: CONCENTRATION vs. TIME
FOR CALCIUM
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

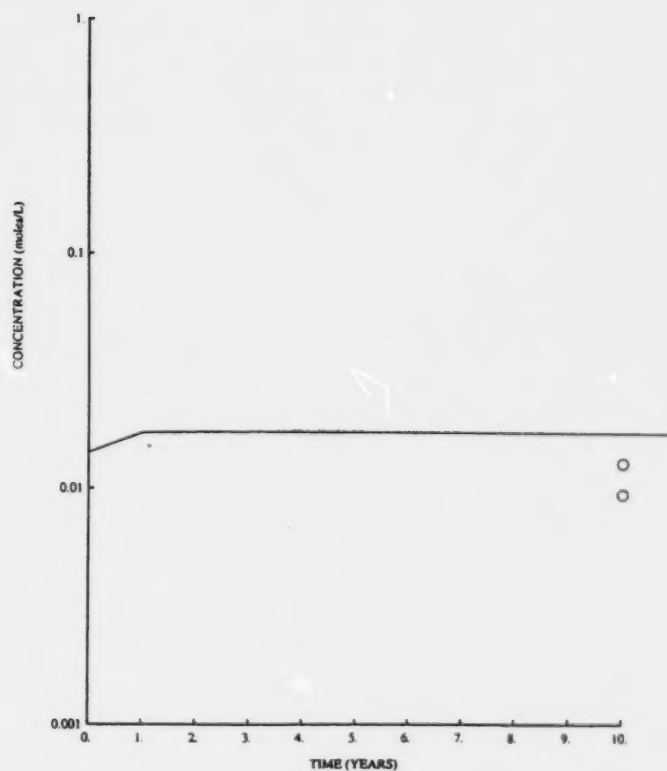


FIGURE 3.4.2: CONCENTRATION vs. TIME
FOR SULPATE
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

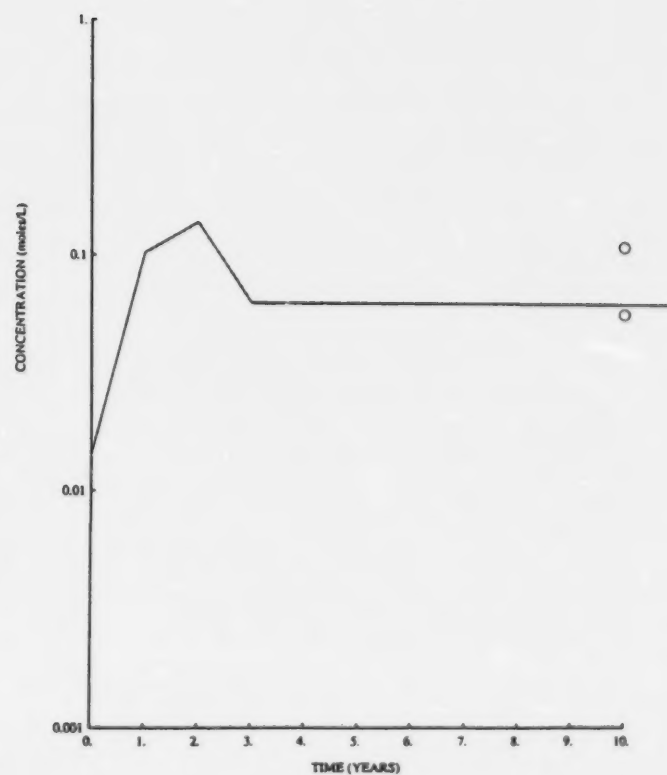


FIGURE 3.4.3: CONCENTRATION vs. TIME
FOR MAGNESIUM
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

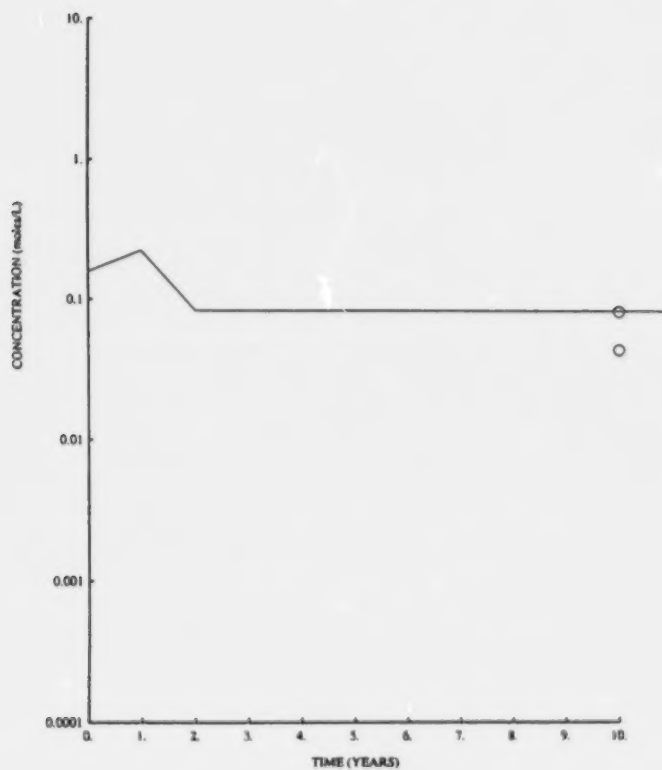


FIGURE 3.4.4: CONCENTRATION vs. TIME
FOR TOTAL CARBONATE
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

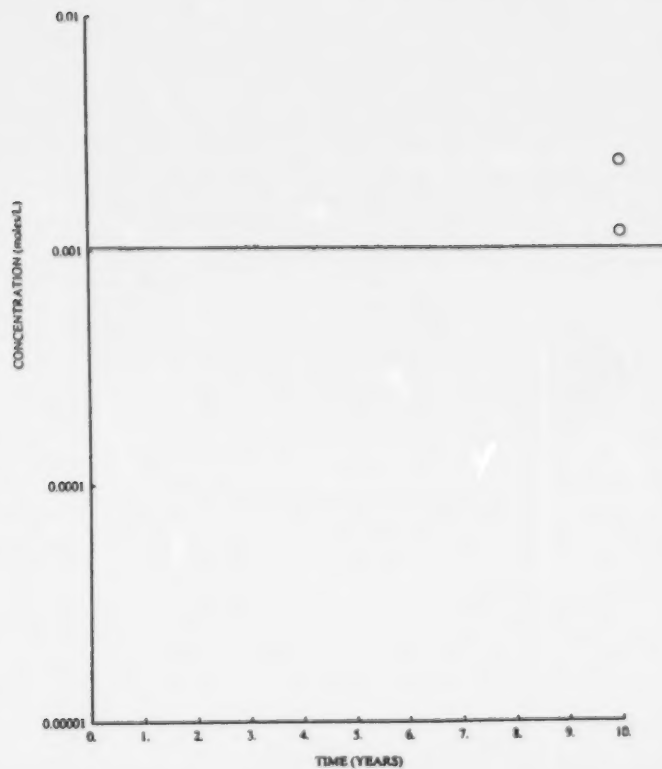


FIGURE 3.4.5: CONCENTRATION vs. TIME
FOR PH
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

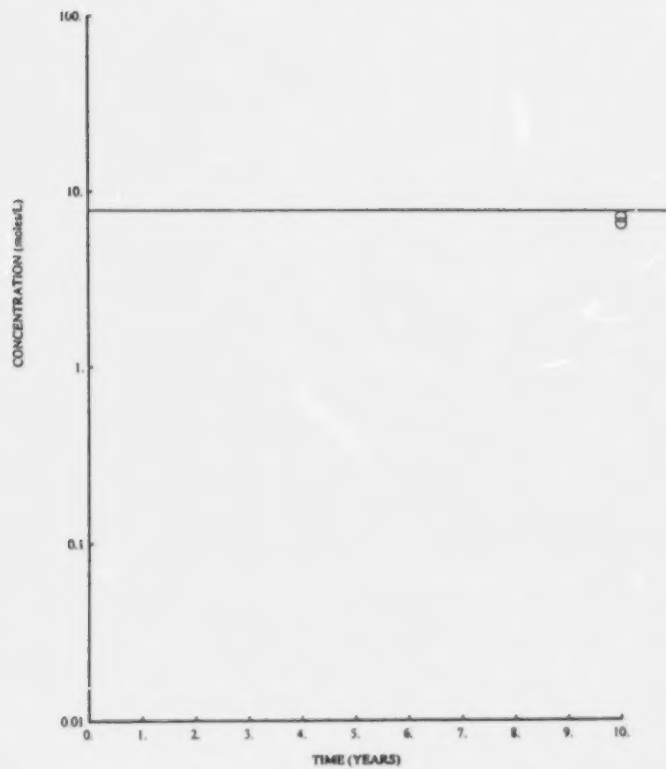


FIGURE 3.4.6: CONCENTRATION vs. TIME
FOR BARIUM
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

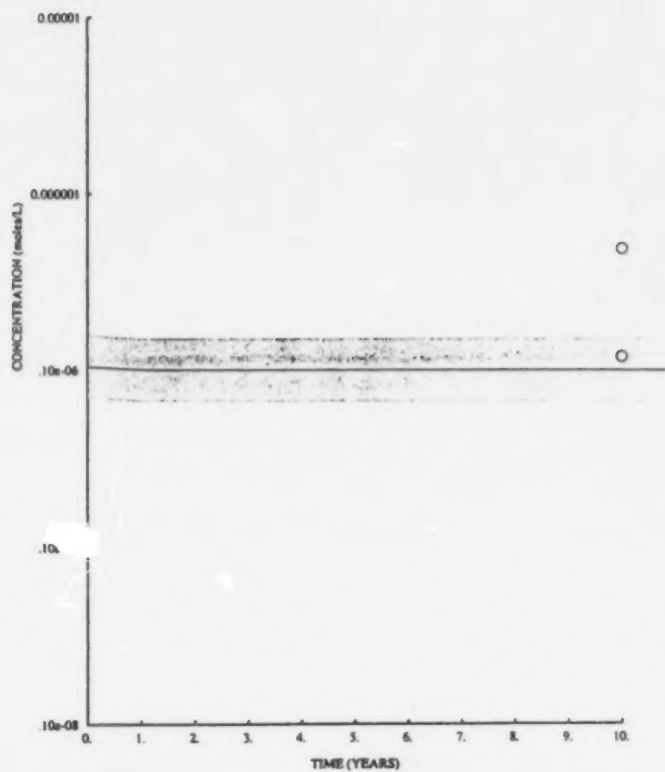


FIGURE 3.4.7: CONCENTRATION vs. TIME
FOR LEAD
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

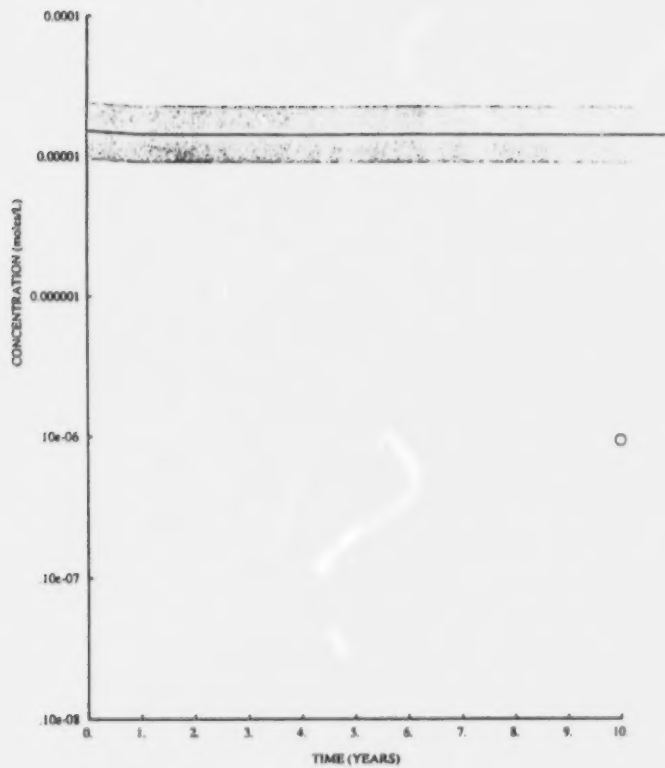


FIGURE 3.4.8: CONCENTRATION vs. TIME
FOR URANIUM
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

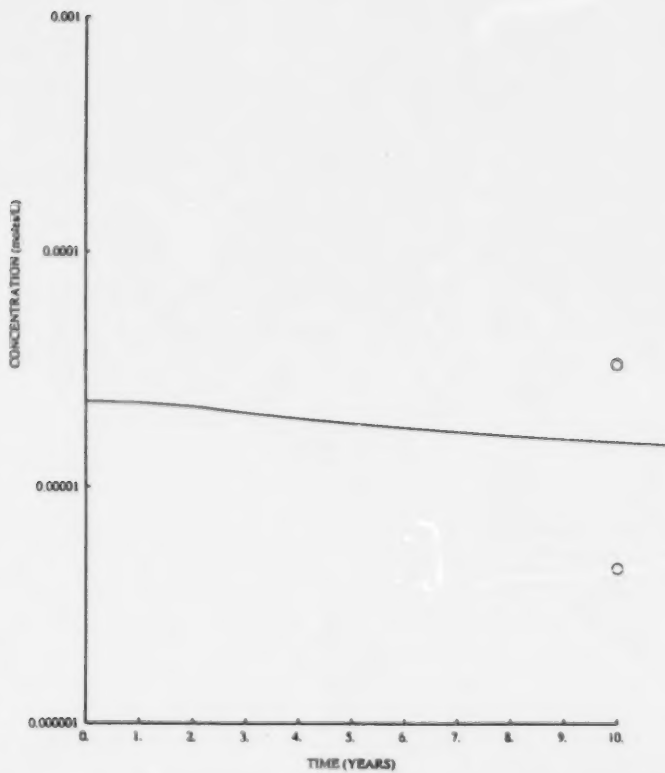


FIGURE 3.4.9: CONCENTRATION vs. TIME
FOR TH-232
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

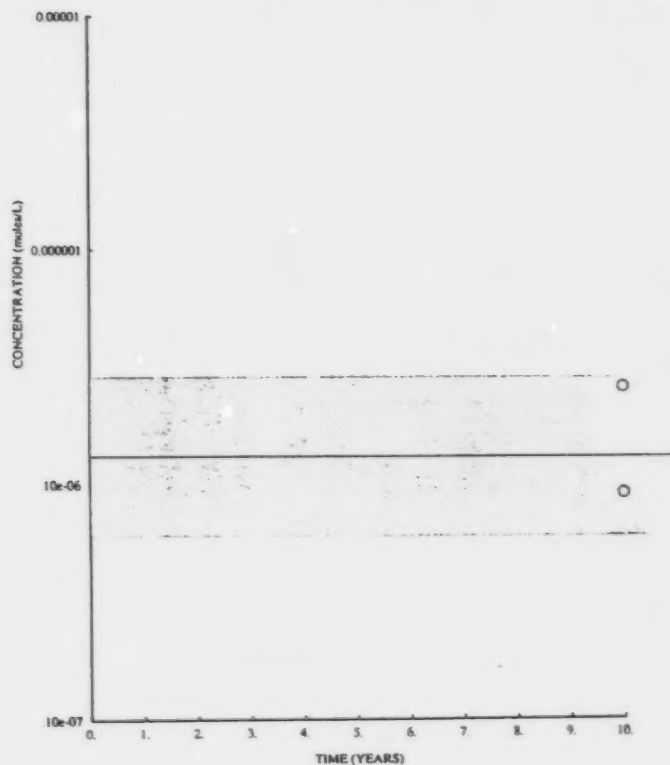


FIGURE 3.4.10: CONCENTRATION vs. TIME
FOR RA-226
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS

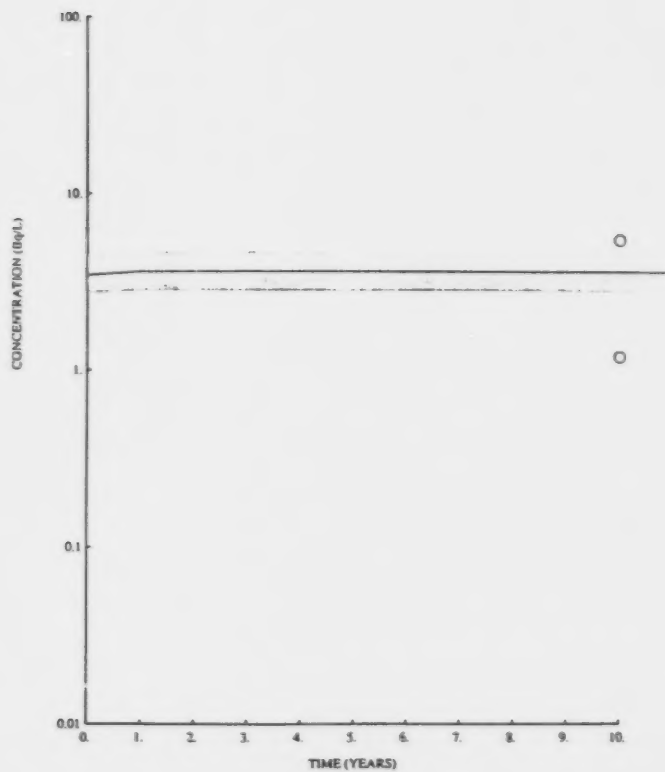
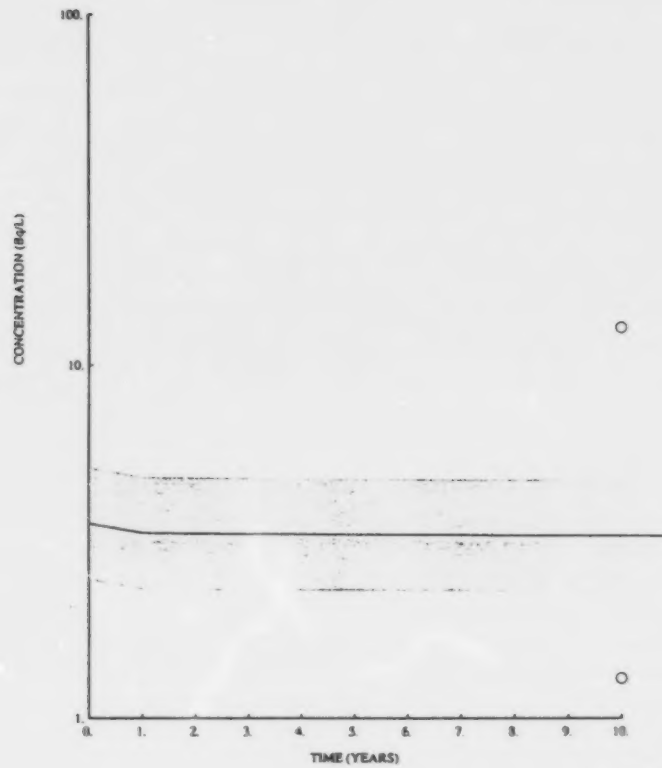


FIGURE 3.4.11: CONCENTRATION vs. TIME
FOR PB-210
FOR SCENARIO 1, IN PORE WATER
GEOMETRIC MEAN OF 5 TRIALS



As well, the mean value of Ra-226 adsorption coefficient was increased to 100 cc/gm from the value of 1 cc/gm used in the BEAK (1986) study. This increase was made to account for the lack of sorption reactions when all minerals which coprecipitate Ra-226 (gypsum, barite, anglesite) wash out. This sorption coefficient is within the range used in the literature, but also continues the modelling philosophy of explaining as much of radium's solid-solution behaviour as possible with coprecipitation theory. The adsorption coefficient is assumed to be a constant value throughout the simulation period, although experimental measurements (BEAK, 1987) suggest that its value is a function of the solution composition. Further work is required to develop predictive models for relating K_D for tailings to the solution composition.

4.0 ENVIRONMENTAL PATHWAYS

4.1 General

The flow of radionuclides from the tailings area to the potential receptors occurs first through aquatic and atmospheric pathways, then through soil systems, vegetation and animals (see Figure 4.1). Exposure of humans occurs:

- o by drinking water, eating plants and consuming fish flesh contaminated with the radionuclides;
- o by inhalation of airborne radionuclides (e.g., radon and nuclides attached to respirable aerosols); and
- o walking on soils contaminated by dustfall.

Damage to human health results from alpha, beta and gamma emissions from radioisotopes ingested and inhaled, and from gamma emission for external exposure.

A generic pathways diagram (Figure 4.1) used for previous pathways studies by BEAK summarizes the movement of radionuclides described above from tailings to the potential human receptor. Also indicated are pathways which are not included in the present assessment. Transport to surface water pathways occurs via groundwater from tailings porewater and via erosion of surficial tailings material. Transport to the atmosphere results from exhalation of gases (radon-222) from the tailings and dust erosion by winds. Crops consumed by humans are contaminated by dustfall. Aquatic plants and fish are contaminated by uptake from lake water and lake sediments. In this study, wild animal pathways (moose, caribou) and consumption of aquatic plants are neglected; the rationale for this is outlined in Chapter 2 and Section 4.4.

Pathways not shown in Figure 4.1 but considered in previous studies include external exposure due to walking on beaches containing contaminated sediment, swimming in lake water and bathing/showering in water contaminated by discharges to surface water pathways (BEAK, 1982; SENES, 1986). The literature (e.g., BEAK, 1982) indicates that the dose received via external exposure from swimming, bathing and beach walking is negligible relative to that from internal pathways. The external exposure characteristics used in these calculations (by BEAK, 1982) were quite conservative. Hence, this pathway is neglected in this assessment.



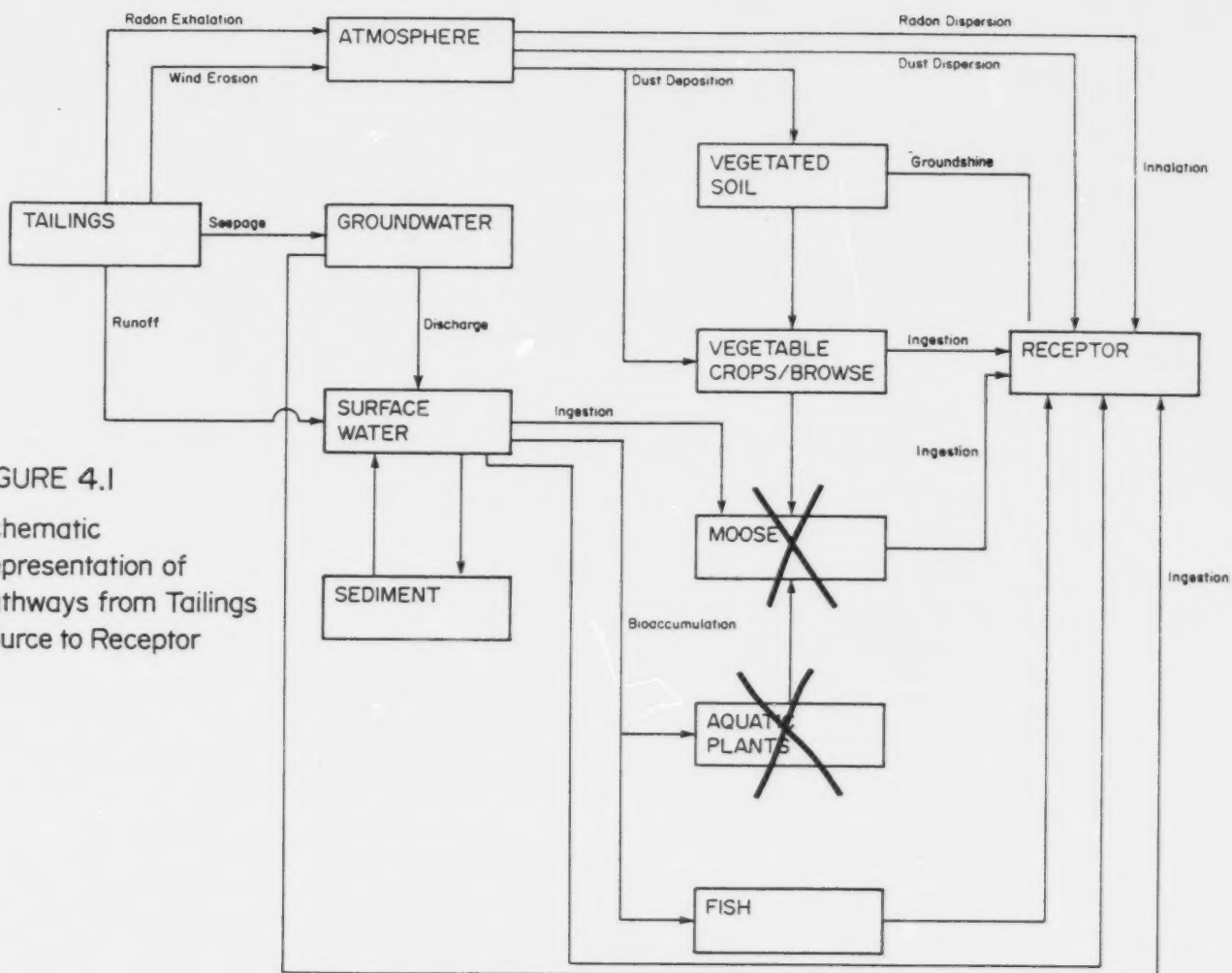


FIGURE 4.1

Schematic
Representation of
Pathways from Tailings
Source to Receptor

External exposure by walking on soils (called groundshine) has only recently been considered in UTAP (SENEs, 1986). It was not considered previously in the demonstration of UTAP for the northern Saskatchewan site (BEAK, 1986), but were considered in the analysis of MacLaren (1986) for the Rabbit Lake site. These two studies (SENEs, 1986; MacLaren, 1986) suggest that groundshine is quite small relative to the dose received from consumption of vegetables by humans and vegetation browsed by animals. This would justify an assumption of neglecting groundshine. However, to check this assumption, groundshine is included in this work.

4.2 Groundwater Pathways

As indicated in the source term description (Section 3.2), tailings porewater is transported to groundwater through the toe of the dam and downward through the peat layer into underlying glacial soils. The results of a groundwater modelling study of tailings seepage from the Rabbit Lake tailings during its operation (GEOCON, 1982) indicate that there are three major seepage directions from the tailings:

- o through the north dam;
- o through the south dam; and
- o across the tailings area from the topographical high on the north side of the tailings through the tailings mass across the intervening field to Parks Lake.

The GEOCON study also suggested that transport under the north and south dam occurred over a depth of 100 m (see Figure 4.2a). Their flow lines suggested that transport under each dam could be abstracted into four major flow tubes for purposes of this probabilistic assessment - one flow tube seeping through the dam as part of the dam drainage system; one flow tube under the dam which surfaces 200 m downstream of the dam; one flow tube which surfaces 800 m downstream of the dam; and one flow tube which enters deeper strata and which does not effectively surface. These tubes are sketched in Figure 4.2b (profile sketch).

For the probabilistic assessment, a total of seven groundwater pathways have been implemented to distribute the tailings seepage through the groundwater. Three pathways flow through the ground from each of the north and south sides of the tailings pile, while the seventh exits in an easterly direction.

INTERPRETATION OF COMPUTER OUTPUT

FIGURE 4.2B Groundwater Flow Pathways

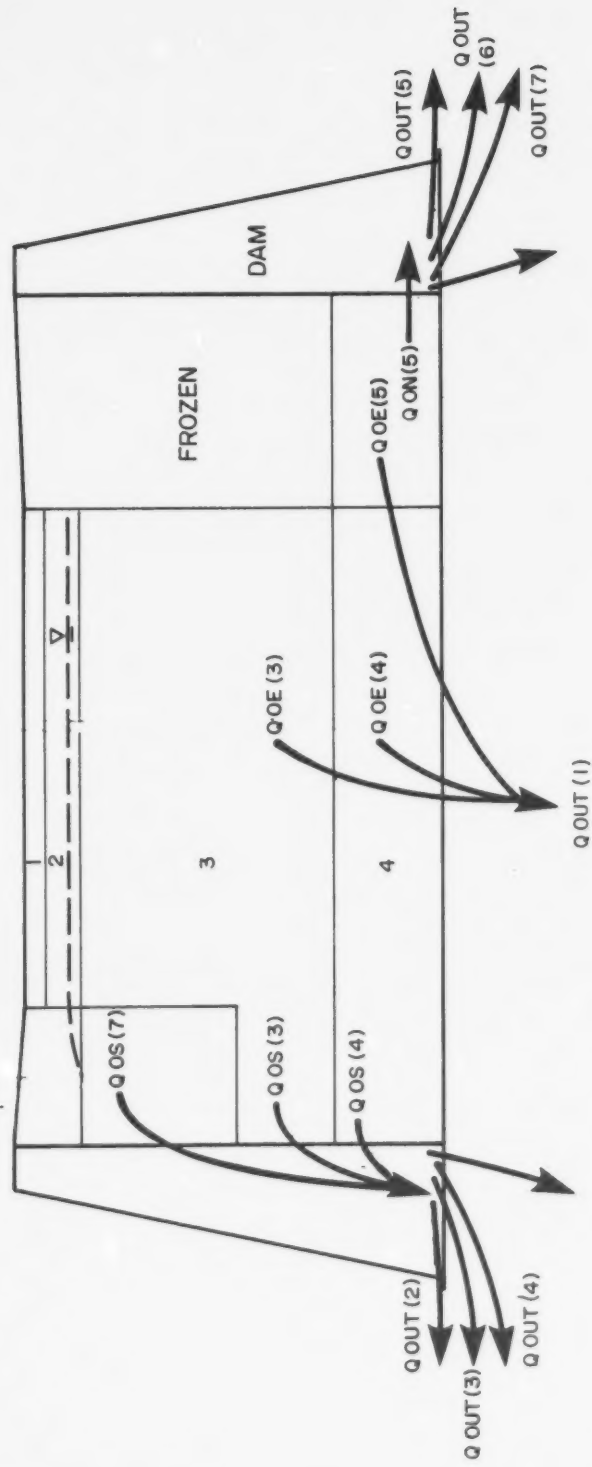


Table 4.1 shows the respective groundwater flow path directions and flow rate contributions from each of the water-saturated boxes in the tailings pile. Path 1 flows from the eastern boundary of the tailings pile, discharging to the surface waters at Parks Lake. The resultant groundwater flow rate is the combined sum of mass balance flow rates exiting in an easterly direction from Boxes 3, 4, 5 and 7.

Paths 2 through 4 account for all flow leaving the tailings in a southerly direction and discharge to surface water which drains into Hidden Bay. Paths 2, 3 and 4 account for groundwater flow through the toe of the southern dam, and water discharging to the surface at 200 and 800 metre distances from the tailings, respectively. Contributions from mass balance flow rates exiting in a southerly direction from Boxes 3, 4 and 7 are listed in Table 4.1. A final portion of flow contributing to the deep (regional) groundwater flow regime is not modelled in the groundwater pathway module, as it does not interact with the modelled receptors.

Groundwater pathways 5 through 7 consider flow rates exiting from the northern dam of the tailings pile, discharging into streams which then drain into Parks Lake. Pathways through the dam toe, and 200 and 800 metre path lengths refer to paths 5, 6 and 7 respectively. The flow rate contributions from boxes in the tailings pile is limited to that exiting in a northerly direction from Box 5. Again, the deep groundwater component in this direction is not modelled.

Each groundwater flow path is modelled using the portion of the Phase III code of SENES (1986) written by SENES for the groundwater pathway. The same code was used for groundwater by BEAK (1986) for the demonstration of UTAP. For the seven groundwater pathways, the subroutine is duplicated seven times, once for each pathway. Interfacing subroutines were written in this project to relate the tailings concentrations and relative flow from each box to each groundwater pathway, and to collect the calculated results from the end of each pathway as input values to the appropriate receiving surface water body.

Parameter values describing adsorption processes of U, Th, Ra-226, Pb-210 and Po-210 in the ground are given in Table 4.2. Other parameter values used in the groundwater model for Rabbit Lake are also summarized in Table 4.2.

TABLE 4.1: DISTRIBUTION OF FLOW FROM INDICATED BOXES TO INDICATED GROUNDWATER PATHWAYS

Path No.	Description	Length (m)	Percentage Contribution from:			
			Box 3	Box 4	Box 5	Box 7
1	East	500	1.0	1.0	1.0	1.0
2	South	toe	0.27	0.27	-	0.27
3	South	200	0.27	0.27	-	0.15
4	South	800	0.19	0.19	-	0.23
5	North	toe	-	-	0.27	-
6	North	200	-	-	0.24	-
7	North	800	-	-	0.20	-

TABLE 4.2: GROUNDWATER MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
Flow Path 1						
X_s	distance along flow path to surface water	m	500	C (500)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m ²	5,000	C (5,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{ps}	longitudinal dispersivity	m	500	C (50)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	kg·m ⁻³	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components:	m ³ kg ⁻¹			INPUT	DCGWAT(I)
	- uranium		0.01	T (0.01, 0.02, 0.03)		
	- thorium		0.25	T (0.25, 0.50, 0.75)		
	- lead		0.50	T (0.50, 0.67, 0.83)		
	- radium		0.05	T (0.04, 0.07, 0.09)		
	- calcium		0	C (0)		
	- sulphate		0	C (0)		
Flow Path 2						
X_s	distance along flow path to surface water	m	75	C (75)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m ²	1,000	C (1,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{ps}	longitudinal dispersivity	m	7.5	C (7.5)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	kg·m ⁻³	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components:	m ³ kg ⁻¹			INPUT	DCGWAT(I)
	- uranium		0.01	T (0.005, 0.01, 0.015)		
	- thorium		0.012	T (0.006, 0.012, 0.024)		
	- lead		0.005	T (0.002, 0.005, 0.008)		
	- radium		0.007	T (0.004, 0.007, 0.01)		
	- calcium		0	C (0)		
	- sulphate		0	C (0)		
Flow Path 3						
X_s	distance along flow path to surface water	m	200	C (200)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m ²	1,000	C (1,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{ps}	longitudinal dispersivity	m	20	C (20)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	kg·m ⁻³	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components:	m ³ kg ⁻¹			INPUT	DCGWAT(I)
	- uranium		0.01	T (0.005, 0.01, 0.015)		
	- thorium		0.012	T (0.006, 0.012, 0.024)		
	- lead		0.005	T (0.002, 0.005, 0.008)		
	- radium		0.007	T (0.004, 0.007, 0.01)		
	- calcium		0	C (0)		
	- sulphate		0	C (0)		

TABLE 4.2: GROUNDWATER MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
Flow Path 4						
X_s	distance along flow path to surface water	m	800	C (800)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m^2	2,000	C (2,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{s_s}	longitudinal dispersivity	m	80	C (80)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	$kg \cdot m^{-3}$	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components: - uranium - thorium - lead - radium - calcium - sulphate	$m^3 kg^{-1}$	0.01 0.012 0.003 0.007 0 0	T (0.005, 0.01, 0.015) T (0.006, 0.012, 0.024) T (0.002, 0.003, 0.008) T (0.004, 0.007, 0.01) C (0) C (0)	INPUT	DCGWAT(I)
Flow Path 5						
X_s	distance along flow path to surface water	m	73	C (73)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m^2	1,000	C (1,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{s_s}	longitudinal dispersivity	m	7.5	C (7.5)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	$kg \cdot m^{-3}$	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components: - uranium - thorium - lead - radium - calcium - sulphate	$m^3 kg^{-1}$	0.01 0.011 0.004 0.006 0 0	T (0.002, 0.01, 0.018) T (0.0033, 0.011, 0.022) T (0.002, 0.004, 0.006) T (0.002, 0.006, 0.01) C (0) C (0)	INPUT	DCGWAT(I)
Flow Path 6						
X_s	distance along flow path to surface water	m	200	C (200)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m^2	1,000	C (1,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_{s_s}	longitudinal dispersivity	m	20	C (20)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	$kg \cdot m^{-3}$	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components: - uranium - thorium - lead - radium - calcium - sulphate	$m^3 kg^{-1}$	0.01 0.011 0.004 0.006 0 0	T (0.002, 0.01, 0.018) T (0.0033, 0.011, 0.022) T (0.002, 0.004, 0.006) T (0.002, 0.006, 0.01) C (0) C (0)	INPUT	DCGWAT(I)

TABLE 4.2: GROUNDWATER MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
Flow Path 7						
X_s	distance along flow path to surface water	m	800	C (800)	INPUT	XRGWAT
A_s	cross-sectional area of groundwater pathway	m ²	2,000	C (2,000)	INPUT	AXGWAT
n_s	porosity of geologic medium along flow path	-	0.33	C (0.33)	INPUT	POGWAT
α_s	longitudinal dispersivity	m	80	C (80)	INPUT	LDGWAT
$S.G._s$	specific gravity of geologic medium solids	kg·m ⁻³	2,650	C (2,650)	INPUT	SGWAT
k_{di}	distribution coefficients for the chemical components:	m ³ kg ⁻¹			INPUT	DCGWAT(I)
	- uranium		0.01	T (0.002, 0.01, 0.018)		
	- thorium		0.011	T (0.0053, 0.011, 0.022)		
	- lead		0.004	T (0.002, 0.004, 0.006)		
	- radium		0.006	T (0.002, 0.006, 0.01)		
	- calcium		0	C (0)		
	- sulphate		0	C (0)		

4.3 Surface Water Pathways

Radionuclides enter surface lakes and streams in three major forms:

1. a soluble form from groundwater seepage and overland flow;
2. particulate form, from erosion of the surface of tailings; and
3. wet fall and dry fall from the atmosphere.

Overland flow is only significant during rainfall events; otherwise, most contaminated flow results from infiltration into the tailings and subsequent seepage through the tailings to surface waters. In the study, transport in soluble form via overland flow is assumed to be negligible.

The source of wet and dry fall to the surface water is tailings material which is eroded from the tailings surface by winds. This is assumed to be negligible.

The major seepage pathways travel directly to Parks Lake and directly to Hidden Bay. All groundwater seepage streams enter into surface streams before discharge to the lakes. Due to the short residence time of the streams, the streams are not considered in this project. As noted above, groundwater flow paths Nos. 1, 5, 6 and 7 go to Parks Lake, while groundwater flow path Nos. 2, 3 and 4 go to Hidden Bay. As well, due to the decommissioned design, surface water (overland flow) from the tailings and eroded particles are carried through the surface stream to Hidden Bay. This flow passes through a small pond/marsh system ("the Duck Pond") prior to entering Hidden Bay.

Water from Parks Lake discharges to Hidden Bay (see Figure 2.1). Water flow from Hidden Bay discharges to Wollaston Lake. As well, currents enter Hidden Bay from Wollaston Lake and return to the lake. Over sufficiently long time scales (weeks to months), these currents can be parameterized as an exchange flow involving a movement of an equal volume of water between the lake and bay on a daily basis. The exchange flow between Hidden Bay and Wollaston Lake will dominate the chemical concentrations of substances in Hidden Bay, although the rate of inflow from the Umpherville River will also be influential. The exchange flow rate, E , will be influenced by the width of the mouth of the bay where it joins the lake, the depth of the mouth, and the variance of water levels within the lake and the bay. The variance of water levels is influenced by

wind conditions, atmospheric pressure variations, and coriolis effects. There are no field measurements available to calibrate the exchange rate. Information from other water bodies shows that E varies from typically one to ten times the annual inflow rate into the bay from land-based sources. A nominal value of 4 is adopted for E in this study as used in the previous UTAP demonstration (BEAK, 1986).

The morphology and hydrology of the surface receiving waters have been estimated in previous studies. The range of estimates is given in Table 4.3. The data for Parks Lake are derived from Saskmont (1980), and are the best estimates available. The data from which this is summarized are given in Appendix D. The data for Hidden Bay are generally consistent except where it is noted that the estimates for Hidden Bay (BEAK, 1986b) include Otter Bay. The Sawchyn (1973) values are adopted for this study. The flow data available for Umpherville River, which indicate a range of detention time of 0.47a to 1.4a for the period 1974 to 1981, are used to give the probabilistic range for the triangular distribution (see Appendix D). The values of Rawson (1959) are used for Wollaston Lake.

The mass balance model used for calculating the radionuclide activity and chemical concentrations in the receiving waters is that of BEAK (1986). The nominal and probabilistic values of model parameters are given in Table 4.4. The only major change required to the model is the impact of suspended solids, eroded from the tailings surface, upon the receiving waters. UTAP.3, the most recent SENES version of UTAP, considers that these eroded particles enter the lake, settle out in the nearshore sediment region, and then are resuspended and carried to deeper lake sediments by lake currents. A different set of assumptions is appropriate here. The eroded sediments are transported from the tailings along the Tailings Creek to the Duck Pond, and then along the Tailings Creek to Hidden Bay. Analysis of a smaller but similar particle size distribution using a hydrology-water quality model, QUALHYMO (BEAK, 1987b) indicates that in excess of 80% of eroded particles would settle out in Duck Pond. Of the particles transported to Hidden Bay, some amount of material will desorb in the water column before these particles settle into the sediments.

In the sediments of Hidden Bay, it is plausible that some of the material would be eroded and subsequently carried to Wollaston Lake. Such erosion would dilute the material in Hidden Bay sediments. The mechanism of erosion and deposition from nearshore

TABLE 4.3: MORPHOMETRY AND HYDROLOGY OF RECEIVING WATERS

	Surface Area	Volume	Detention Time	Mean Depth	Reference
Parks Lake	1.58 km ²	5.18x10 ⁶ m ³	1.6 yr	3.3 m	Saskmont (1980)
Hidden Bay- Otter Bay	-	7.72x10 ⁸ m ³	3 yr	-	BEAK (1986b)
Hidden Bay	20.99 km ²	1.44x10 ⁸ m ³	0.78 yr*	6.9 m	Sawchyn (1973)
Hidden Bay	21.83 km ²	1.09x10 ⁸ m ³	0.59 yr*	5 m	SGS (1976)
Wollaston Lake	2,080 km ²	4.24x10 ¹⁰ m ³	14 yr**	20.4 m	BEAK (1986b)
Wollaston Lake	796 mi ² (2,063 km ²)	3.62x10 ¹⁰ m ³	14 yr***	17.4 m	Rawson (1959)

* Calculated using average flow from Umpherville River of 207.2 cfs.

** This value is given in BEAK (1986) appendix. Using BEAK (1986) data of Figure D3.1 (see appendix) which indicates that flow in Cochrane River is 170 m³/s and flow in Fond du Lac River is 6 m³/s, the residence time is 7.6 years.

*** Estimated by Rawson, assuming 2,700 cfs for Cochrane River and 270 cfs for Fond du Lac River. This, however, gives a residence time of 16 years.

sediments is difficult to model and to calibrate without field data. SENES have developed a model for this phenomenon in UTAP.3. Less transport from a bay to a lake may normally be expected than transport from nearshore to offshore sediments. To be conservative, for the Hidden Bay receptor, it is assumed that the eroded tailings remain in the sediments of Hidden Bay.

To estimate the amount of radionuclides desorbed from the tailings particles into the water column, the rate of desorption and the settling time in the water column must be known. Laboratory tests (see Table 3.1.1 and BEAK, 1987) indicated that less than 0.2% of Ra-226 was desorbed in 24 hours using distilled water as a washing agent. A nominal fraction of Th-230 will desorb because of solubility control upon Th-232. It is assumed that 0.1% of all radionuclides desorb from the tailings solids during their time in the water column of Hidden Bay assuming a time for settling of one day. This settling velocity is higher than that used for other particles in the lake, but these other particles have a lower intrinsic settling velocity because they are organic. A triangular distribution with a range of 0.05% to 0.2% is used as for the fraction of radionuclides released in the water column.

The kinetics used in the lake model and its calibration require checking (i.e., validation studies). However, available data for Wollaston Lake area are not sufficient to permit a thorough evaluation of the lake model. Some aspects of sediment-water transport can be evaluated. Radionuclide concentrations from sediment cores in four lakes in the vicinity of Wollaston Lake (Collins Bay, Hidden Bay, Upper Link Lake, Dutting Site) were collected. Sediment data from two cores were modelled using a diffusion-adsorption model (Neame *et al.*, 1982). Two sediment models were used: Model 1 uses an analytical solution for diffusion and adsorption ($K_d = 5,000$), while Model 2 uses a finite difference model. The comparison of observed and calculated concentrations for the 0 to 1 cm layer are given in Table 4.5 (uranium and Ra-226). Values for Th-230 were generally less than 0.5 pCi/g. The results indicate that neither model came close to explaining the observed data for Hidden Bay after six years of simulation. This suggests that diffusion alone is inadequate to explain the transport of uranium and Ra-226 into sediments, and that both sedimentation and diffusion must be employed to explain sediment-water interactions. The results for Hidden Bay suggest that diffusion might explain approximately 10% and settling 90% of the observed sediment concentrations.

TABLE 4.4: LAKE PARAMETERS

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
SS	suspended solids concentration	mg·L ⁻¹	1	U (0.5, 1)	INPUT	SS(1) SS(2) SS(3)
K _D	adsorption coefficient: - U - Th-230 - Ra-226 - Pb-210 - Po-210	mL g ⁻¹	500 50,000 200 1,000 1,000	T (250, 500, 750) T (25,000, 50,000, 75,000) T (100, 200, 300) T (500, 1,000, 1,500) T (500, 1,000, 1,500)	INPUT	KDLAK(1) KDLAK(2) KDLAK(3) KDLAK(4) KDLAK(5)
Z	lake mean depth: - Lake 1 - Lake 2 - Lake 3	m	3.3 6.9 17.4	C (3.3) C (6.9) C (17.4)	INPUT	ZLAK(1) ZLAK(2) ZLAK(3)
A	lake area: - Lake 1 - Lake 2 - Lake 3	m ²	1.58E6 20.99E6 2.06E9	C (1.58E6) C (20.99E6) C (2.06E9)	INPUT	ALAK(1) ALAK(2) ALAK(3)
t _w	detention time: - Lake 1 - Lake 2 - Lake 3	years	1.6 0.78 14	T (0.8, 1.6, 2.0) T (0.47, 0.78, 1.4) T (8, 12, 16)	INPUT	TW(1) TW(2) TW(3)
alp	exchange coefficient: - Lake 1 - Lake 2 - Lake 3	-	0 4 0	C (0) U (0.1-6.0) C (0)	INPUT	ALPHA(1) ALPHA(2) ALPHA(3)
por	sediment porosity: - Lake 1 - Lake 2 - Lake 3	-	0.95 0.95 0.95	C (0.95) C (0.95) C (0.95)	INPUT	POR SED(1) POR SED(2) POR SED(3)
g	particulate settling velocity: - Lake 1 - Lake 2 - Lake 3	m·a ⁻¹	25 25 25	T (15, 25, 35) T (15, 25, 35) T (15, 25, 35)	INPUT	G(1) G(2) G(3)
k _s	mass transfer coefficient: - U - Th-230 - Ra-226 - Pb-210 - Po-210	m·a ⁻¹	4 4 4 4 4	T (2, 4, 6) T (2, 4, 6) T (2, 4, 6) T (2, 4, 6) T (2, 4, 6)	INPUT	FKS(1) FKS(2) FKS(3) FKS(4) FKS(5)
g _s	sedimentation rate: - Lake 1 - Lake 2 - Lake 3	m·a ⁻¹	0.001 0.001 0.001	T (0.0002, 0.0005, 0.0020) T (0.0002, 0.0005, 0.0020) T (0.0002, 0.0005, 0.0020)	INPUT	GS(1) GS(2) GS(3)
k	radioactive decay rate: - U-238 - Th-230 - Ra-226 - Pb-210 - Po-210	a ⁻¹	1.5E-10 8.7E-6 4.27E-4 0.034 1.83	C (1.50E-10) C (8.664E-6) C (4.273E-4) C (3.397E-2) C (1.83)	INPUT	RADIOD(1) RADIOD(2) RADIOD(3) RADIOD(4) RADIOD(5)
f _{pmd}	fraction of eroded material settling in duck pond	-	0.9	T (0.85, 0.9, 0.95)	INPUT	FPOND
f _{desorb}	fraction of tailings entering lake desorbed and water column	-	0.001	T (0.0005, 0.001, 0.002)	INPUT	FDSORB
W ₀	loading	Bq·a ⁻¹ or g·a ⁻¹ or mol·a ⁻¹	-	-	calculated	W
C	activity or concentration in lake or embayment	Bq·L ⁻¹ ; g/m ⁻³ ; mol·L ⁻¹	-	-	calculated	CLAK(I,K)
C _s	activity or concentration in lake sediments	Bq·L ⁻¹ ; g·m ⁻³ ; mol·L ⁻¹	-	-	calculated	CSED(I,K)

Lake 1: Parks Lake.

Lake 2: Hidden Bay.

Lake 3: Wollaston Lake.

TABLE 4.5: COMPARISON OF OBSERVED AND PREDICTED URANIUM ($\mu\text{g/g}^{-1}$) and RADIUM-226 (pCi/g^{-1}) CONCENTRATIONS IN SURFACE SEDIMENT (0 to 1 cm layer; after Neame et al., 1982)

Parameter	Location	Observed	Models Predicted by	
			Model 1	Model 2
Uranium	Hidden Bay	326	0.07	0.11
	Upper Link Lake*	5,650	0.07	0.11
Radium-226	Hidden Bay	5.3	0.12	0.38
	Upper Link Lake*	931	4.9	15.9

* Comparison by Neame et al. (1982) is inappropriate for Upper Link Lake due to contamination of sediments by direct tailings discharge.

Substantial care must be taken in evaluating the comparison of Neane et al. (1982) for Upper Link Lake because the Upper Link Lake sediments were contaminated by highly concentrated tailings effluent and probably by tailings solids. Accordingly, the comparison is completely inappropriate.

4.4 Atmosphere

4.4.1 Dust

Dust, containing U-238 decay chain radionuclides, is generated by wind erosion of uncovered tailings. Windblown dust is carried downwind to the receptor where it may be inhaled or deposited on soils which produce food for the receptor. No dust is assumed to be generated for the covered tailings scenarios.

The dust model used in this assessment is the formulation used by BEAK (1986), which calculates the erosion rate as a function of silt content, wind velocity and duration, Thornthwaite's precipitation-evaporation (PE) index, vegetation cover, the number of "wet" days per year and an erodibility constant.

Silt is calculated as the initial fine fraction in the tailings surface plus any new silt formed by weathering of coarser fractions, minus the silt removed as dust. The silt content of the coarser surface tailings, based on Borehole No. 1 (GEOCON, 1986) is 4 to 44% silt. The silt content at any time is calculated by a silt subroutine, as described by BEAK (1986).

The vegetation factor, V, accounts for the reduction in tailings erodibility due to natural growth of vegetation over the tailings surface. Data from the Gunnar tailings site suggest that, over time, uncovered tailings will gradually become overgrown with native plants. Complete coverage may never be achieved on the Rabbit Lake tailings surface owing to persistent unfavourable conditions in some areas. It is impossible to foresee the rate of coverage of the Rabbit Lake tailings over the long-term, since data on plant growth on uncovered tailings in northern Saskatchewan are extremely limited, and are representative of only the first few years after site closure. For this assessment, we use a similar assumption to the one made by BEAK (1986) in the non-pyritic tailings demonstration of UTAP. That is, V is set at 1.0 (no vegetation and hence maximum

potential erodibility) initially, and is assumed to decrease to a final value of 0.001 at time T_m , which is assumed to range between one and four centuries.

Data in NRCC (1982) indicate that the annual PE index ranges between 40 and 50 in northern Saskatchewan. As in the UTAP demonstration for a non-pyritic tailings (BEAK, 1986), the PE index is estimated to have a triangular distribution for Rabbit Lake, with a minimum of 35, a mode of 45 and a maximum of 55.

The erodibility factor, e , is dependent on the nature of the tailings. Based on the data given on particle size distribution data by GEOCON (1986), the coarser zone of surficial Rabbit Lake tailings may be classified as sandy clay to sand. This description will apply to the entire surface area after close-out. This zone can be assigned an erodibility index value of about 0.6, based on the data given in Table B5.1.1 of BEAK (1986).

The initial tailings bulk density, RHO_T , is nominally $1.14 \times 10^6 \text{ g/m}^3$ for the coarser zone of the Rabbit Lake tailings (Table 2.2).

The annual number of "wet" days, defined as the number of days with more than 0.25 mm of precipitation, was calculated from the AES STAR data for Collins Bay.

The Phase III version of UTAP incorporates a dust reduction factor to account for a suppression of wind erosion under winter conditions. Observations at Rabbit Lake in winter indicate that dust is generated under these conditions in areas that do not cover with ice and snow, although some winter reduction is judged to occur. Here it is assumed that a 50 to 75% reduction in dust erosion occurs during the six months of freezing conditions at Rabbit Lake.

Erosion of material from the permafrost zone would be important if the proposed decommissioning option (shaping the surface to cover with new solids) were not employed. There is some uncertainty concerning the depth of freezing and thawing of the surface of a permafrost zone. It could be assumed that the surface tailings layers responsible for atmospheric releases evolve geochemically in the same manner in the remaining tailings area. This would be due to the seasonal thawing of the tailings surface over all of the tailings surface, and the transport of tailings porewater downslope along the permafrost layer toward the concave centre of the tailings mass. Thus, tailings

solids in the permafrost zone would maintain the same radionuclide concentrations as surface solids in the unfrozen area. Due to the decommissioning design, it is assumed that the surface cover is thick enough that neither wind erosion nor gullying due to water runoff remove the cover down to the permafrost zone. Accordingly, geochemical reactions in the permafrost zone are not modelled in this assessment.

Table 4.6 gives a summary of parameter values and distributions used in the Dust subroutine.

4.4.2 Radon

Gaseous radon is formed from the radioactive decay of Ra-226. Once formed, Rn-222 emanates from the solid and liquid phases into the gaseous phase, and diffuses according to its concentration gradient. The portion of Rn-222 which does not diffuse out of the tailings decays in situ to particulate Pb-210. Dispersion of Rn-222 released to the atmosphere is controlled by atmospheric processes and by radioactive decay.

The radon model used in this assessment is the same as the model used by BEAK (1986) and similar to that used by SENES (1986). The surface (unsaturated) layer of the Rabbit Lake tailings is modelled as an upper barium sulphate-depleted zone (with a reduced radium content), and a lower barium sulphate-enriched zone (with a higher radium content). Only the portion of the Rabbit Lake tailings that is not in permafrost is modelled in this manner.

The flux of radon from the tailings is calculated as a function of the tailings surface area, the radon diffusion coefficient, Ra-226 concentration, the emanation coefficient, tailings density, the radon decay constant, the thickness of the unsaturated tailings layers, porosity, moisture content and the number of months with freezing conditions. Many of these parameters are calculated as described in the non-pyritic case demonstration of UTAP (BEAK, 1986).

The porosity of Rabbit Lake tailings is estimated to be about 0.55 after consolidation (Table 2.2). The moisture content of the tailings is estimated at 47% (Table 2.2). As there are no estimates of the emanation coefficient for Rabbit Lake tailings, the value applied in the BEAK (1986) study, derived from data in Strong and Levins (1982) and the

TABLE 4.6: ATMOSPHERIC SOURCE MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
DUST						
$Q_{ij}(t)$	emission rate of the <i>i</i> th radionuclide in area <i>j</i> at time <i>t</i>	$Bq \cdot s^{-1}$	calculated	calculated	DUST	EMRATE(I)
<i>S</i>	silt content of the tailings (% of particles $> 75 \mu m$)	%	calculated	calculated, initial value $N(4, 44)$	SILT	SILT
<i>f</i>	percentage of the time that the wind speed exceeds 5.4 m/s at the mean tailings height	%	calculated	calculated	WIND	FWINDT
$C_{ij}(t)$	surficial concentration of <i>i</i> th radionuclide in area <i>j</i> at time <i>t</i>	$Bq \cdot g^{-1}$	calculated	calculated	SOURCE	CTOT(I,J)
$A_j(t)$	exposed surface area of the tailings in area <i>j</i> at time <i>t</i>	m^2	calculated	calculated	DUST	AEXPT
RHO_T	tailings bulk density	$g \cdot m^{-3}$	1.14×10^6	initialized and then calculated	SILT	RHOT(I,J)
R_{WEATH}	weathering rate of coarse fraction	yr^{-1}	0.001	T (0.0003, 0.00075, 0.001)	INPUT	RWEATH
<i>T_m</i>	time when tailings are completely vegetated	year		U (100, 400)	INPUT	TCUTOF
<i>e</i>	soil erodibility	-	0.6	T (0.25, 0.6, 0.98)	INPUT	EI
<i>V</i>	fractional due to vegetation reduction in wind erosion	-	calculated	calculated	DUST	VEGERD
<i>PE</i>	Thornthwaite's Index	-	0.45	T (0.35, 0.45, 0.55)	INPUT	PE
<i>RF</i>	reduction factor to account for decreased erosion in winter	-	-	U (0.5, 0.75)	INPUT	RF
<i>N_w</i>	number of months of freezing conditions			U (6, 7)		FROZ
RADON						
<i>a</i>	Reciprocal of radon diffusion length of tailings	m^{-1}	calculated	calculated	RADON	DIFLEN
<i>D</i>	effective bulk radon diffusion coefficient of tailings	$m^2 \cdot s^{-1}$	calculated	calculated	RADON	EBKDFC
<i>E</i>	radon emanation coefficient of tailings	-	0.2	T (0.02, 0.2, 0.9)	INPUT	EMANAT
$J_1(t)$	radon flux from non-permafrost zone	$Bq \cdot m^{-2} \cdot s^{-1}$	calculated	calculated	RADON	RNFLUX
<i>M</i>	percent moisture content by weight of tailings	-	calculated	calculated	INPUT	MPCH20
<i>P</i>	porosity of tailings	-	0.4	T (0.5, 0.55, 0.6)	INPUT	POR(I)
$(Ra)_i(t)$	radium concentration of layer <i>i</i> = 1 or 2	$Bq \cdot m^{-3}$	calculated	initialized then calculated	SOURCE	CTOT(I,15)
$x_1(t)$	thickness of box 1	<i>m</i>	0.1	C (0.1)	INPUT	DEPTH1
$x_2(t)$	thickness of box 2	<i>m</i>	2.9	C (2.9)	INPUT	DEPTH2
	radon decay constant	s^{-1}	2.1×10^{-6}	C (2.1×10^{-6})	INPUT	RNLAM
A_0	exposed surface area of the unfrozen tailings at time <i>t</i>	m^2	$5.5E5$	C (5.5E5) (at <i>t</i> = 0 for base case)	INPUT	ATAIL
<i>R</i>	frozen/unfrozen flux ratio	-	0.1	T (0.02, 0.1, 0.18)	INPUT	RFROZ
A_p	surface area of the permafrost zone of tailings (for sensitivity analysis only)	m^2		C (1.7E5)	INPUT	ATAILP
<i>FR</i>	radon flux/Ra-226 activity ratio (for sensitivity analysis only)	$(Bq \cdot m^{-2} \cdot s^{-1}) / (Bq \cdot g^{-1})$	0.1	LU (0.002, 0.6)	INPUT	FLXRAT
$J_2(t)$	radon flux from permafrost zone	$Bq \cdot m^{-2} \cdot s^{-1}$	calculated	calculated	RADON	RNFLUXP
$J_{tot}(t)$	total radon flux	$Bq \cdot m^{-2} \cdot s^{-1}$	calculated	calculated	RADON	RNFLUXI

U.S. NRC (1980), is applied here. The mode of the emanation coefficient applied here (0.2) is also the emanation coefficient that has been observed by Eldor Mines in nearby Eagle Point tailings.

In the phase III version of UTAP (SENES, 1986), provision for a reduction in radon emission rates due to freezing has been incorporated. As noted by SENES, freezing conditions have been shown to attenuate the radon flux due to the smaller radon diffusion coefficient in ice relative to water. Measurements by Zettwoog et al. (1981) demonstrated reduction factors of 3, 100 and 400 for tailings with moisture contents of less than 10%, 30% and saturation, respectively. Based on several measurements of radon flux, the frozen/unfrozen flux ratio for Gunnar tailings is about 0.1. Similar frozen/unfrozen flux ratios have been observed at Beaverlodge for relatively dry tailings, although lower ratios were found in a wet beach area. The average annual flux, J_{avg} , is given by:

$$J_{avg} = J (N_w R + (12 - N_w)) / 12$$

where: N_w is the number of winter months per year (six to seven months for Rabbit Lake), and

R is the frozen/unfrozen flux ratio, nominally 0.1.

In a sensitivity analysis, it was assumed that surficial tailings over the permafrost portion of the tailings did not undergo the geochemical evolution occurring over the unfrozen area, and that Ra-226 activities in the surficial layer in the permafrost zone remained constant over the modelling period. In this case, radon fluxes from the portion of the tailings that is permanently frozen will differ from fluxes occurring over the unfrozen portion. In the permafrost area, the tailings surface will thaw seasonally to a depth of several centimetres, while the underlying tailings remain frozen. In this situation, radon fluxes from the permafrost zone are calculated based on radon flux-Ra-226 activity ratios measured in the Gunnar tailings, as summarized in Table 4.7. These data suggest that the frequency distribution of these ratios is log-uniform, with the ratio ranging between 0.002 and 0.6 for Gunnar. These flux ratios are assumed to apply to the permafrost zone of the Rabbit Lake tailings during non-winter conditions. The average annual flux, J_{avg} , for the permafrost area of the Rabbit Lake tailings is calculated as outlined earlier. The results of the sensitivity analysis (not given) indicated that the

TABLE 4.7: RADON FLUXES* AND Ra-226 ACTIVITIES IN SURFICIAL TAILINGS AT GUNNAR

Radon Monitoring Site	Radon Flux (Bq/m ² ·s)	Ra-226 Activity** (Bq/g)	Flux/Activity Ratio
C3	2.97	7.0	0.42
C3	4.00	7.0	0.57
C3	3.09	7.0	0.44
C8	0.87	67	0.013
C8	0.13	67	0.002
C8	1.48	67	0.022
M2	1.4		
M2	0.56		
M2	2.3		
M3	1.7	7.0	0.24
M3	0.56	7.0	0.08
M3	2.3	7.0	0.33
M4	1.3	30	0.04
M4	1.3	30	0.04
M4	2.8	30	0.09
M4	1.9	30	0.06
M5	1.5		
M5	1.2		
M5	1.4		
M5	0.96		
M6	1.4		
M6	1.8		
M7	1.7		
M7	0.19		
M7	1.8		
M7	1.0		
M8	0.48	67	0.007
M8	4.4	67	0.066
M8	1.6	67	0.024
M9	1.4		
M9	4.8		
M10	1.3	14.5	0.09
M10	1.4	14.5	0.10
M11	5.6		
M12	1.3		
M12	2.0		
M13	2.3		

* For non-winter conditions only. Suspect results excluded.

** Values selected as representative of radon monitoring sites from Gunnar field studies.

geochemical evolution or lack thereof of the permafrost zone had a small effect on the overall dose calculations.

For the waste rock cover management case, the waste rock will also be a radon source. The total surface area of the existing waste rock will not be appreciably altered by removal of a relatively small fraction to cover the tailings. Thus, spreading of the waste rock over the tailings will increase the exposed waste rock surface area from the facility by roughly the area of the tailings mass, and the waste rock cover is considered an incremental source of radon to the atmosphere. The rate of exhalation of radon from Rabbit Lake waste rock is unknown. In Gunnar waste rock, radon activities in the pore spaces of the rock pile ranged from about 200 to 400 pCi/L (7 to 15 Bq/L), but the exhalation rate was not determined. In an open pit area of an Australian uranium mine, a relatively stable radon exhalation rate of $80 \text{ Bq}\cdot\text{m}^{-2}\cdot\text{sec}$ per percentage of U_3O_8 was measured (UNSCEAR, 1982). This rate of exhalation may also be expected in waste rock. With an average grade of 0.015% U_3O_8 , the exhalation rate of radon from the waste rock at Rabbit Lake will be about $1.2 \text{ Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Table 4.6 summarizes parameters and values applied in the RADON source subroutine.

4.4.3 Air Dispersion Model

Once released from the tailings, airborne dust and radon are carried downwind in directions and speeds controlled by local meteorological conditions. This is modelled using the same sector-averaged Gaussian plume model developed by SENES for Phases I, II and III studies (SENES, 1984, 1985, 1986), and applied in the non-pyritic UTAP demonstration (BEAK, 1986).

A virtual source setback correction factor, required to account for the area-source nature of the atmospheric release, is now calculated for a 16-sector model within the air dispersion (AIRDIS) subroutine in the Phase III version of UTAP applied herein.

In Phase III of UTAP, the vertical dispersion coefficient, σ_z , is calculated as a function of downwind distance to the receptor, according to power law coefficients for the atmospheric stability classes, as read from the Environment Canada STAR data files. Power law coefficient values are as listed by SENES (1986) for atmospheric stability classes A to F. The same nominal 2 m source height is also assumed to apply.

AIRDIS uses the atmospheric data in the STAR file to predict dispersion characteristics. The Rabbit Lake study area has been divided into 16 sectors and five radial distances to produce 80 potential receptor locations, as outlined by SENES (1986). Radial distances are set at 1, 6, 9, 18, 27 and 36 km. Rings 1, 2, 3, 4 and 5 are thus respectively located at distances of 1-6, 6-9, 9-18, 18-27 and 27-36 km from the tailings. The first receptor, Wollaston Post, is located about 32 km to the east of the tailings, and is thus within sector 5 and ring 5. The second receptor at Hidden Bay is situated about 7 km south-southwest of the tailings, and is within sector 11 and ring 2.

UTAP-Phase III has the capability of calculating area-weighted average air concentrations for modelling inputs to soil and terrestrial vegetation, which are in turn used in estimating uptake by game animals (moose and caribou) which may range widely throughout the study area or throughout specific watersheds and beyond. Because foraging animals are not considered on this application, no area-weighted average air concentrations are calculated.

AIRDIS parameter values appropriate for Rabbit Lake are listed in Table 4.8.

4.4.4 Wind Model

Subroutine WIND calculates the required atmospheric stability, wind speed and wind direction data required by AIRDIS for calculating atmospheric concentrations of radon and particulate radionuclides. The required wind data are computed from the 14-year meteorological database available on the Collins Bay STAR file from Environment Canada, as detailed in the SENES (1986) Phase III documentation.

4.5 Soil Model

The Phases I and II UTAP codes contained no models to evaluate soil compartments and subsequent uptake by vegetation or groundshine. In the non-pyritic tailings demonstration, BEAK (1986) incorporated a simple soil model into the Phase II code to account for settling of airborne dust, incorporation into the surface soil layer, and uptake by plants. The Phase III version of UTAP incorporates a more complex soil model that evaluates:

TABLE 4.3: AIR DISPERSION MODEL VARIABLES

Symbol	Description	Units	Nominal Value	Statistics	Source	Computer Symbol
$C_i(t)$	atmospheric concentration of i th radionuclide at time t at receptor	$Bq \cdot m^{-3}$	calculated	calculated	AIRDIS	AIRC(5,j)
f_{kl}	fraction of time wind blows from source to receptor in section k with atmospheric stability l	-	calculated	calculated	WIND	FWIN2(k,l)
h	source height	m	2.0	U (1.0,3.0)	INPUT	HSRC
$Q_i(t)$	emission rate of i th radionuclide at time t	$Bq \cdot s^{-1}$	calculated	calculated	RADON DUST	EMRATE(5)
$\bar{u}_i$	mean annual wind speed	$m \cdot s^{-1}$	calculated	calculated	WIND	UWIND(k,l)
x	downwind distribution to receptor	m	calculated	calculated	C/M	RNGMID(x)
z	vertical dispersion coefficient	m	calculated	calculated	AIRDIS	VIDSP(x,6)
A_0	total surface area of tailings	m^2	5.5E5	C (5.5E6)	INPUT	ATAIL

- o deposition of incoming airborne radioactivity;
- o leaching of radioactive elements from the surface soil;
- o runoff of radionuclides in solution; and
- o radioactive decay and ingrowth.

The Phase III model is used in this application. A description of the model equations and symbols are given in SENES (1986).

Soils of the Rabbit Lake region are described as humo-ferric podsols, with stoney and rocky phases being common. These soils tend to be acidic ($\text{pH} < 5$), with variable quantities of sand and clay-sized particles. The Rabbit Lake mine is located at the eastern edge of the Athabasca sedimentary basin, and the tailings management area is located beyond the limits of the Athabasca sandstone, on metamorphic rocks of the Upper Wollaston Group. These rocks are overlain by relatively thin glacial deposits which vary both laterally and vertically. The stratigraphy of these deposits is complex, and includes a variety of glacial tills, eskers, drumlins, outwash deposits, as well as recent lacustrine and peat deposits.

Phase III of UTAP uses a multi-layered model to predict soil concentrations of radionuclides. The surface layer receives atmospheric fallout, and loses radioactivity due to leaching to the second layer or due to runoff. The second layer then loses radioactivity due to decay and to leaching to a deeper layer. Once in the deeper layer, the radioactivity is assumed to be lost from the biosphere (i.e., is below the root layer), but will contribute an extremely small increment to groundshine. For the Rabbit Lake application, we assume that the surficial organic layer is 5 cm thick, that the second layer is 15 cm thick (consisting mainly of soil horizon B), and that the third deepest layer is 0.01 to 2 m deep. Data on overburden depth at the two receptor locations have not been collected, but soils are recognized as very shallow, particularly at Wollaston Post.

SENES (1986) applied K_d values for a wide range of soil types in their Phase III development, but suggested that site-specific K_d values could be used for specific UTAP applications.

BEAK conducted adsorption experiments using glacial till subsoils and marshy organic deposits near the Rabbit Lake tailings. Soil suspensions were mixed with solutions of

gamma-emitting Th-234, Ra-224 and Pb-203, and K_d 's determined by gamma spectrometry of the remaining solids and solutions. The results listed in Table 4.9 are used in the soil model (Table 4.10) to describe K_d values for the surface layer (based on the marshy soils) and for the two subsurface layers (based on the glacial till). Values for polonium are assigned equal to values for lead.

For uranium, no site-specific K_d values are available. The extremely wide range given in SENES (1986) probably incorporates some precipitation or ion exchange effects. The range given in Johnston and Gillham (1980) is considerably lower, and is applied herein for Rabbit Lake soils.

The fraction of net precipitation that enters local groundwater at the receptor will vary seasonally, annually and spatially within any receptor area. Wang *et al.* (1978) determined that recharge to groundwater is 1 to 24% of total precipitation in the Shield. These values would be larger percentages of net precipitation. Net precipitation is nominally 44% of total precipitation, based on data extrapolated from the Hydrological Atlas of Canada. Thus, recharge to groundwater in Rabbit Lake soils is assumed to have a uniform distribution, from 2 to 55% of net precipitation.

The dry bulk density of the surface layer of soil is assumed to have the same statistical attributes as the soil surface layer described by SENES (1986). For the second, 15-cm deep layer, a particle density of 2.0 to 2.5 g/cm³ and a porosity of 0.6 are assumed, giving a bulk density of 0.8 to 1.0 g/cm³. The third layer is assumed to be more compacted, with a porosity of about 0.5 and the same particle density as the second layer, giving a dry bulk density of 1 to 1.2 g/cm³.

Net precipitation data for Rabbit Lake is calculated from Environment Canada data on total precipitation at Collins Bay, reduced by 250 mm per year to account for the evapotranspiration rate that is typical of the region, as shown in the Hydrological Atlas.

Table 4.10 lists the appropriate soil subroutine parameter values and distributions used in this application. An elaboration on model equations and variables is given in SENES (1986).

TABLE 4.9: K_D VALUES (mL/g) FOR RABBIT LAKE SOILS*

Soil Type	Experiment	Th	K_D	Pb
	No.		Ra	
Glacial Till	25	2,569	9,277	12,614
	26	-	10,006	14,295
	29	1,626	7,736	5,300
	30	1,320	7,265	4,876
Organic (Marshy) Soils	33	3,954	10,191	6,307
	34	-	11,664	10,542

* Based on tracer experiments using gamma-emitting Th-234, Ra-224 and Pb-203.

TABLE 4.10: SOIL MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
B_{ij}	variable in activity equation	yr^{-1}	calculated	calculated	SOIL	BETAI
B_{oij}	variable in activity equation	$\text{Bq}\cdot\text{yr}^{-1}$	calculated	calculated	SOIL	BETAO(I,J)
C_{Ain}	concentration of ith radionuclide in nth windrose sector	$\text{Bq}\cdot\text{m}^{-3}$	calculated	calculated	AIRDIS	AIRC(N,I)
V_g	deposition velocity	$\text{m}\cdot\text{s}^{-1}$	0.0163	$U(0.003, 0.03)$	INPUT	DEPVEL
D_j	depth of soil layer j	m			INPUT	ZSOIL(J)
	o Layer 1		0.03	$C(0.03)$		
	o Layer 2		0.15	$C(0.15)$		
	o Layer 3			$U(0.01, 2.0)$		
F	fraction of net precipitation resulting in runoff	-	0.263	$U(0.02, 0.53)$	INPUT	FWAT
λ_i	decay constant for ith radionuclide	yr^{-1}			INPUT	LAMDA(I)
	o Uranium		1.53×10^{-10}	$C(1.53 \times 10^{-10})$		
	o Thorium		4.92×10^{-11}	$C(4.92 \times 10^{-11})$		
	o Lead		3.3×10^{-2}	$C(3.3 \times 10^{-2})$		
	o Radium		4.33×10^{-4}	$C(4.33 \times 10^{-4})$		
	o Polonium		1.83×10^0	$C(1.83 \times 10^0)$		
P	net precipitation	$\text{m}\cdot\text{yr}^{-1}$	253	$N(0.253, 0.114, 0.030, 0.43)$	INPUT	NPRCP
ρ_j	bulk density of jth soil layer	$\text{kg}\cdot\text{m}^{-3}$			INPUT	RHOS(J)
	o Layer 1		129	$LN(129, 1.3, 20, 430)$		
	o Layer 2		900	$U(800, 1,000)$		
	o Layer 3		1,100	$U(1,000, 1,200)$		
K_{dij}	distribution coefficient for jth soil layer and ith radionuclide	$\text{m}^3\cdot\text{kg}^{-1}$	253	$LN(1,241, 1.1, 1,000, 1,800)$	INPUT	SOILKD(I,J)
	j = 1 Uranium		0.1	$U(0, 0.3)$		
	Radium		10.9	$U(9, 13)$		
	Lead, Polonium		8.4	$U(5, 12)$		
	Thorium		4	$U(2, 6)$		
	j = 2,3 Uranium		0.1	$U(0, 0.3)$		
	Radium		8.6	$U(7, 11)$		
	Lead, Polonium		9.3	$U(4, 15)$		
	Thorium		1.8	$U(1, 2.6)$		
C_{wijr}	water concentration of radionuclide i in soil layer j for receptor R	$\text{Bq}\cdot\text{m}^{-3}$	calculated	calculated	SOIL	SWCONC(R,J,I)
W_j	water content of jth soil layer	$\frac{\text{kg (water)}}{\text{kg}^{-1} \text{ (soil)}}$			INPUT	WC(J)
	o Layer 1		0.23	$U(0.1, 0.3)$		
	o Layer 2		0.23	$U(0.1, 0.3)$		
	o Layer 3		0.33	$U(0.2, 0.5)$		
$Z_{ijr}(t)$	activity of radionuclide i in soil layer j for receptor R	Bq	calculated	calculated	SOIL	ZTOT(I,J,R)
$Z_{ijr}(t_0 - t)$	activity of radionuclide i in soil layer j at receptor R at beginning of time interval	Bq	calculated	calculated	SOIL	ZZERO(I,J,R)

4.6 Terrestrial Vegetation Models

Consumption of vegetation by the critical group represents a route for radionuclide ingestion. In Wollaston Post, there are only four vegetable gardens, each covering an area of about 10 m^2 . Only lettuce and potatoes are grown due to soil and climatic limitations. It is estimated that these vegetables are grown in sufficient quantities to support consumption by a family of four over two months of the year. Wollaston Post residents also consume considerable quantities of wild berries - approximately seven one-gallon buckets (about 30 L) per family of four per year.

Uptake of radionuclides by vegetation is modelled for root crops (potatoes) and above-ground crops (lettuce and berries). Uptake by lichen and summer forage consumed by game animals is not modelled, as game animals are not hunted in the study area.

The Phase II version of UTAP predicts plant tissue concentrations based entirely on atmospheric fallout and deposition on edible portions. In the non-pyritic tailings demonstration, BEAK (1986) added an uptake from soil components to the calculation. This latter form of the subroutine is also included in UTAP - Phase III, and is applied in the Rabbit Lake assessment.

Table 4.11 lists the variables used in the vegetation uptake component model (VEGCON) for Rabbit Lake. Values for V_d , E_v , F_{rv} , t_v and λ_{wv} for vegetation were allowed to vary uniformly around the values recommended by the U.S. NRC (1982), with the exception of t_v for wild berries, which was taken as the value recommended by BEAK (1985f) for browse in northern Saskatchewan. Values for vegetation yield, Y_v , were varied uniformly around values recommended by BEAK (1985).

In the non-pyritic tailings demonstration of UTAP, BEAK (1986) reviewed literature on soil-to-plant transfer coefficients (B_v 's) to derive appropriate parameter distributions for above- and below-ground vegetables. These values are applied here for the calculation of soil-to-plant transfer in the three vegetation types consumed at Rabbit Lake receptors.

TABLE 9.11: VEGETATION UPTAKE MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
$C_{air}(t)$	atmospheric concentration of ith radionuclide in area R at time t	$Bq \cdot m^{-3}$	calculated	calculated	AIRDIS	CAIR(R,I) (I = 1-5) (R = 1-2)
$C_{vijk}(t)$	concentration of radionuclide in receptor area j and vegetation type k	$Bq \cdot g^{-1}$	calculated	calculated	VEGCON	CVEG(R,K,I) (R = 1-2) (I = 1-5) (K = 1-3)
F_{rvk}	fraction of total deposition retained on surface of vegetation: o above-ground vegetables (k = 1) o below-ground vegetables (k = 2) o berries (k = 3)		0.2 0.2 0.2	U (0.1, 0.3) U (0.1, 0.3) U (0.1, 0.3)	INPUT	FDEPSF(K) FDEPSF(1) FDEPSF(2) FDEPSF(3)
E_{vk}	fraction of deposition retained on edible portions: o above-ground vegetables (k = 1) o below-ground vegetables (k = 2) o berries (k = 3)		1.0 0.1 1.0	U (0.8, 1.0) U (0.05, 0.15) U (0.8, 1.0)	INPUT	FDEPED(K) FDEPED(1) FDEPED(2) FDEPED(3)
t_{vk}	duration of exposure to deposition o above-ground vegetables (k = 1) o below-ground vegetables (k = 2) o berries (k = 3)	s	5.184E6 5.184E6 7.8E6	U (4.7E6, 5.6E6) U (4.7E6, 5.6E6) U (6.8E6, 8.8E6)	INPUT	DUREXP(K) DUREXP(1) DUREXP(2) DUREXP(3)
V_d	deposition velocity	$m \cdot s^{-1}$	0.02	U (0.003, 0.03)	INPUT	DEPVEL
Y_v	yield density: o above-ground vegetables (k = 1) o below-ground vegetables (k = 2) o berries (k = 3)	$g \cdot m^2$	2,000 2,000 100	U (1,500, 2,500) U (1,500, 2,500) U (75, 125)	INPUT	YDEN(K) YDEN(1) YDEN(2) YDEN(3)
wv	decay rate accounting for weathering loss: o above-ground vegetables o below-ground vegetables o berries	s^{-1}	3.73E-7 3.73E-7 3.73E-7	U (4E-7, 7E-7) U (4E-7, 7E-7) U (4E-7, 7E-7)	INPUT	VEGLAM(K) VEGLAM(1) VEGLAM(2) VEGLAM(3)
B_v	soil-to-plant concentration factors for three vegetable types: o U o Th o Ra o Pb o Po	$(Bq \cdot g^{-1} w.w.)^{-1}$ $(Bq \cdot g^{-1} d.w.)^{-1}$		LN(1.9E-3, 11, 1.0E-3, 5.5E-1) LN(3.9E-3, 13, 5.0E-4, 2.5) LN(6.0E-3, 8.1, 8.0E-3, 7.0E-1) LN(1.3E-2, 5.2, 7.0E-3, 1.3E-1) LN(2.2E-2, 12, 2.0E-4, 3.5E-1)	INPUT	BV(K,I) (K = 1-3) BV(K,1) BV(K,2) BV(K,3) BV(K,4) BV(K,5)
P_g	soil density	$g(d.w.) \cdot m^{-3}$	calculated	calculated	VEGCON	RHODRY
$C_{gir}(t)$	concentration of ith radionuclide in soil root zone in receptor area j at time t	$Bq \cdot m^{-3}$	calculated	calculated	SOIL	CSOIL(I,R)

Symbols ww = wet weight; dw = dry weight.

4.7 Aquatic Biota Model

The aquatic biota model is required to describe radionuclide concentrations in fish in Hidden Bay and in Wollaston Lake. Local populations are not known to consume locally grown aquatic plants such as wild rice or watercress.

As in UTAP Phase III and earlier versions, fish tissue concentrations are calculated as a function of the concentration in the water phase using the bioconcentration factors (BCF's) appropriate for each radionuclide. BEAK (1987c) recently compiled a Canada-wide database on fish tissue concentrations of U-238 decay chain radionuclides. For the Rabbit Lake application, BCF values were computed from this database for lake whitefish, lake trout, and for all species in Saskatchewan, as summarized in Appendix D. BCF values for the most studied radionuclides (Ra, U) were found to be log-normally distributed, while distributions for other radionuclides were less well-defined due to the relatively low number of data points. The databases on Wollaston Lake were judged to provide an inadequate basis for the formulation of site-specific BCF's, due to their poorly defined distributions. For the Rabbit Lake evaluation, we have elected to use a set of BCF values calculated for all species of fish in Saskatchewan, with water or tissue concentrations reported as less than detection limits ignored in the BCF calculation. A summary of BCF values and distributions for fish in Saskatchewan is given in Table 4.12.

The dependence of catch on lake pH, as described by SENES (1986), was found to be unnecessary for the Rabbit Lake application, since tailings porewater pH measurements were consistently circumneutral and predicted pH found to be essentially constant over time.

4.8 Dosimetry (Subroutine DOSEIN)

4.8.1 Introduction

Subroutine DOSEIN calculates the annual, average whole body dose equivalent commitment (herein called the average annual dose, or simply dose) for one receptor at Hidden Bay and a second at Wollaston Post.

TABLE 4.12: WATER TO AQUATIC BIOTA MODEL VARIABLES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
B_{fi}	water-to-fish transfer coefficient for radionuclide i: o U o Th o Ra o Pb o Po	$(Bq \text{ or } \mu g) \cdot g^{-1} \cdot w \cdot y \cdot$ $/(Bq \text{ or } \mu g) \cdot m^{-3}$	1.3E-6 1.2E-6 9.5E-6 1.35E-5 8.5E-6	LN(1.3E-6, 11.1, 1E-8, 4E-4) LN(1.2E-6, 5.9, 4.7E-7, 2E-4) LN(9.5E-6, 45.7, 2.7E-7, 1.0E-3) LN(1.35E-5, 40.6, 7.5E-7, 2.4E-4) LN(8.5E-6, 42.9, 1.3E-6, 2.0E-4)	INPUT	BF(I) BF(1) BF(2) BF(3) BF(4) BF(5)
$C_{wir}(t)$	concentration of radionuclide i in Wollaston Lake and Hidden Bay at time t	$(Bq \text{ or } \mu g) \cdot m^{-3}$	calculated	calculated	LOADLK	CWATER(R,I) (R = 1-2) (I = 1-5)
C_{fir}	concentration of radionuclide i in fish flesh from waterbody R	$(Bq \text{ or } \mu g) \cdot g^{-1}$	calculated	calculated	AQBIOTA	CFISH(R,I) (R = 1-2) (I = 1-5)

Hidden Bay is the location of a fishing camp. The receptor group that is modelled consists of the guides and caretakers assumed to inhabit the facility for the ice-free season (approximately five months) (the critical receptor). Doses received by sport fishermen who may use the camp for one or two week fishing trips would be a small fraction of the dose received by camp personnel.

At Wollaston Post, all individuals are essentially year-round residents and are modelled as average individuals practising the life style that is now typical in the community.

The inhalation and ingestion models involve two main aspects: calculation of the receptor's annual intake and multiplication of the intake by a dose conversion factor (DCF). The only sources of dietary intake are fish, water, vegetables and berries. Airborne dust and radon account for the inhalation dose. External doses due to gamma radiation from ground-deposited radionuclides are calculated in the Groundshine Subroutine.

The DCF's used are those appropriate for calculating doses based on stochastic (zero threshold) effects. Non-stochastic doses received by individual organs are not calculated, as thresholds for non-stochastic effects are not approached by critical groups living near uranium mining and milling operations. DCF's have been compiled by the ICRP-30 (1979) and by Johnson and Dunford (1983) for U-238 decay chain radionuclides. Values from the two sources are in close agreement if the same solubility for radionuclides in the stomach and in the lung are assumed to apply. For this assessment, we have adopted the DCF's given by Johnson and Dunford (1983) for U-238, Ra-226, Pb-210 and Po-210 for ingestion (most soluble forms) and inhalation (least soluble forms). The DCF for radon and daughters is derived in the "Inhalation Dose" subsection.

The dose conversion factors for ingestion of thorium isotopes have recently been reviewed by Dr. J.R. Johnson of the Chalk River Nuclear Laboratories. Based on this review, Johnson (pers. comm.) determined that a gut-to-blood transfer factor (F_1) of 0.005 is generally appropriate for routine dietary intake. This would result in a committed effective dose equivalent (H50) of 3.5×10^{-6} Sv/Bq for Th-230 consumed by adults, a value 25 times greater than the 1.4×10^{-7} given by the ICRP (1979) and Johnson and Dunford (1983) for dietary Th-230 based on an F_1 of 0.0002. While the higher H50 value may be more accurate, the lower value is at present much more widely accepted.

TABLE 4.13: VARIABLES USED IN THE CALCULATION OF ANNUAL DOSE AND INTAKES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
VEGETATION MODEL						
$d_{vir}(ing)(t)$	annual whole body dose due to vegetable v ingestion for ith radionuclide at receptor r	$Sv \cdot yr^{-1}$	calculated	calculated	DOSEIN	VGDOSE(I,R) (i = 1-3) (r = 1-2)
$DCF_i(ing)$	whole body DCF for ingestion of element i - U - Th - Ra - Pb - Po	$Sv \cdot Bq^{-1}$ ($Sv \cdot ug^{-1}$ for U)	2.0E-9 3.3E-6 3.2E-7 1.6E-6 3.3E-7	C(2.0E-9) U(1.4E-7, 3.3E-6) C(3.2E-7) C(1.6E-6) C(3.3E-7)	INPUT	DCFING(I) i = element DCFING(1) DCFING(2) DCFING(3) DCFING(4) DCFING(5)
U_{vr}	average annual intake of r = 1, 2 vegetable type v: leafy vegetables below-ground vegetables above-ground fruits and vegetables	$g \text{ (wet weight)} \cdot yr^{-1}$	14E3 79E3 110E3	C(14E3) C(79E3) C(110E3)	VEGDEP	VEGINA VEGINB VEGINC
$C_{vir}(t)$	concentration of element i in vegetation type v at receptor r o leafy vegetables - U o below-ground vegetables - Th o above-ground fruits and veg. - Pb o above-ground fruits and veg. - Po	$Bq \cdot g^{-1}$ ($ug \cdot g^{-1}$ for U)	calculated	calculated	VEGDEP	CVEG(I,V,R) _i (i = 1-3) (v = 1-3) (r = 1-2)
R_v	fraction on vegetable type v after food preparations: o leafy vegetables o below-ground vegetables o above-ground fruit and vegetables		0.83 0.75 0.43	T(0.7,0.83,0.96) U(0.5,1.0) T(0.7,0.83,0.96)	INPUT	FACTA FACTB FACTC
L_{vr}	fraction of vegetable type v grown locally by receptor r o leafy vegetables o below-ground vegetables o above-ground fruit and vegetables o leafy vegetables o below-ground vegetables o above-ground fruit and vegetables	r = 1 Hidden Bay r = 2 Wollaston Post	0 0 0.003 0.17 0.17 0.03	C(0) C(0) U(0,0.01) U(0.12,0.22) U(0.12,0.22) T(0.035,0.03,0.063)	INPUT	FLOCA(1) FLOCB(1) FLOCC(1) FLOCA(2) FLOCB(2) FLOCC(2)
DRINKING WATER MODEL						
$d_{wir}(ing)(t)$	whole body dose commitment due to ingestion of radionuclide i in drinking water at receptor r	$Sv \cdot yr^{-1}$	calculated	calculated	DOSEIN	WATDOS(I,R) (i = 1-3) (r = 1-2)
U_w	average annual water intake	$m^3 \cdot yr^{-1}$	0.6	C(0.6)	INPUT	WATIN
$C_{swik}(t)$	average concentration of element i in drinking water from waterbody k - U - Th - Ra - Pb - Po	$Bq \cdot m^{-3}$ or $ug \cdot m^{-3}$	calculated	calculated	LAKE	CDRINK(I,K) (i = 1-2) CDRINK(I,K) CDRINK(2,K) CDRINK(3,K) CDRINK(4,K) CDRINK(5,K)
L_{wr}	fraction of annual water consumption that is local for receptor r r = 1 Hidden Bay r = 2 Wollaston Post		0.4 1.0	U(0.3, 0.5) U(0.9, 1.0)	INPUT	FWAT(r) OF(1) OF(2)
C_{swik}	average concentration of element i in drinking water from waterbody k	$(Bq \text{ or } ug) \cdot m^{-3}$	calculated	calculated	FCUNIT	CWATER(I,K) (i = 1-3) (k = 1-2)
FISH INGESTION MODEL						
$d_{fir}(ing)(t)$	whole body dose commitment due to ingestion of radionuclide i in fish flesh at receptor r	$Sv \cdot yr^{-1}$	calculated	calculated	DOSEIN	FISHDS(I) (i = 1-3) (r = 1-2)
U_f	average annual intake of fish	$g \cdot yr^{-1}$	100E3	U(75E3, 125E3)	INPUT	FISHIN

TABLE 4.13: VARIABLES USED IN THE CALCULATION OF ANNUAL DOSE AND INTAKES

Symbol	Description	Units	Nominal	Probabilistic	Source	Computer Symbol
C_{fik}	average concentration of element i in fish in waterbody k - U - Th - Ra - Pb - Po	$\text{Bq}\cdot\text{g}^{-1}$ ($\mu\text{g}\cdot\text{g}^{-1}$ for U,As,Ni)	calculated	calculated	AQBIOTA	CFISH(I,K) CFISH(I,K) CFISH(2,K) CFISH(3,K) CFISH(4,K) CFISH(5,K)
L_{fr}	fraction of fish intake from local source for receptor r $r = 1$ Hidden Bay $r = 2$ Wollaston Post	- 0.4 1.0	- 0.4 1.0	U (0.3,0.5) U (0.9,1.0)	INPUT	FPISH(R)
HBFISH	fraction of fish from local sources taken at Hidden Bay by the HB receptor		0.2	U (0.1,0.3)	DOSEIN	HBFISH
INHALATION MODEL (Particulates)						
$d_{lr}(\text{inh})(i)$	whole body dose commitment due to inhalation of radionuclide i at receptor r	$\text{Sv}\cdot\text{yr}^{-1}$	calculated	calculated	DOSEIN	XINDOS(I,R) ($I = 1-3$) ($R = 1-2$)
$DCF_i(\text{inh})$	whole body DCF due to inhalation of radionuclide i - U - Th - Ra - Pb - Po	$\text{Sv}\cdot\text{Bq}^{-1}$ ($\text{Sv}\cdot\mu\text{g}^{-1}$ for U)	1.0E-6 8.1E-5 2.6E-6 3.3E-6 2.3E-6	C (1.0E-6) C (8.1E-5) C (2.6E-6) C (3.3E-6) C (2.3E-6)	INPUT	DCFINH(I) DCFINH(I) DCFINH(2) DCFINH(3) DCFINH(4) DCFINH(5)
U_a	annual inhalation rate	$\text{m}^3\cdot\text{yr}^{-1}$	8,400	C (8,400)	INPUT	XINHIN
$C_{air}(i)$	average air concentration of element i at receptor r - U - Th - Ra - Pb - Po	$\text{Bq}\cdot\text{m}^{-3}$ ($\mu\text{g}\cdot\text{m}^{-3}$ for U,As,Ni)	calculated	calculated	AIRDIS	CAIR(I,R) ($I = 1-3$, $R = 1-2$) CAIR(1,R) CAIR(2,R) CAIR(3,R) CAIR(4,R) CAIR(5,R)
OF_r	fraction of year at receptor location r $r = 1$ Hidden Bay $r = 2$ Wollaston Post	- 0.4 1.0	- 0.4 1.0	U (0.3,0.5) U (0.9,1.0)	INPUT	OF(R) ($R = 1-2$)
INHALATION MODEL (Radon)						
$d_{Rnr}(\text{inh})(i)$	whole body dose commitment due to inhalation of radon plus daughters at receptor r	$\text{Sv}\cdot\text{yr}^{-1}$	calculated	calculated	DOSEIN	RNDOS(R) ($R = 1-2$)
F	equilibrium factor for radon daughters to radon		0.3	T (0.2,0.5,0.8)	INPUT	FRN
INNOC _r	indoor occupancy factor for receptor r $r = 1$ $r = 2$	- 0.6 0.73	- 0.6 0.73	T (0.3,0.6,0.7) T (0.63,0.73,0.85)	INPUT	RNNOC(R) ($R = 1-2$)

For this application, we have assigned a uniform distribution for the Th-230 ingestion DCF ranging between the two values.

4.8.2 Ingestion Dose

1. Annual Dose due to Vegetation Intake

The average annual dose due to consumption of vegetation is calculated as described in SENES (1986) and BEAK (1986). The dose for each of the two receptors (r) from vegetation consumption is a function of the annual intake of each type of vegetation (v), U_{vr} , the concentration of each radionuclide (i) in the vegetation, C_{vij} , the fraction of intake that is from a local (contaminated) source, L_{vr} , and the fraction of the activity remaining after food preparation (e.g., washing, R_v).

Only lettuce and potatoes are grown locally within the Rabbit Lake study area. At present, only four vegetable gardens exist in Wollaston Post; these cover an area of about 10 m^2 each. The harvest from each garden is sufficient to support a family of four for two months. Due to limitations imposed by the local environment, it is not anticipated that these agricultural practices will be appreciably expanded in the future. It is not anticipated that seasonal Hidden Bay residents would cultivate garden crops for visiting fishermen nor for guides.

Wild berries are picked in relative abundance by residents of the Post, and some are frozen for year-round consumption. The typical family of four consumes an estimated seven gallons of berries annually. This volume of berries weighs about 22 kg, and the average quantity consumed per capita is about 5.5 kg. It is reasonable to assume that Hidden Bay residents would also consume some of these berries.

The annual consumption rates of lettuce, potatoes and berries, U_{vr} , are set at 14, 79 and 110 kg/a, respectively, based on the average consumption rates recommended in CSA (1986) for leafy vegetables, root crops and fruits and vegetables. These rates are assumed to apply for both potential receptors.

The fraction of intake that is from local sources, L_{vr} , varies depending on the receptor. For Hidden Bay, seasonal residents are expected to consume a few local berries, but may

not be expected to cultivate vegetables. For Hidden Bay, we have selected an L_{vr} for berries with a uniform distribution around 0.005, corresponding to 0.55 kg/a. For Wollaston Post, L_{vr} for berries is given a triangular distribution, with the mode set at 0.05, corresponding to the average consumption of 5.5 kg/a. For leafy vegetables and potatoes, L_{vr} values are given uniform distributions around nominal values of 0.17, corresponding to one-sixth of the average annual consumption of these vegetables.

The fraction of radionuclide remaining after food preparation, R_v , was reported by Dave et al. (1985) to be about 0.83 due to washing of berries picked downwind of uranium tailings. The relatively low rate of removal was attributed to the sharp tailings particles tending to embed in the fruit. R_v is assumed to vary around this value for berries and leafy vegetables at Rabbit Lake. For potatoes, R_v was chosen to vary between 0.5 and 1.0. The lower value for root crops is that recommended by the U.S. NRC (1982), and the upper value was added in recognition of the uncertainty of this parameter. Parameter values for calculating doses from vegetable intakes are given in Table 4.13.

2. Annual Dose due to Fish Intake

The local Rabbit Lake receptor populations consume considerable quantities of freshwater fish. Wollaston Post residents typically consume eight whitefish per person weekly. Assuming that each whitefish, once filleted, weighs about half a pound, annual per capita consumption is estimated at nominally 100 kg. Greater short-term rates of consumption may be assumed for the fishing camp at Hidden Bay, although residency is seasonal. Hidden Bay residents are assumed to take roughly 30% of their total catch from Hidden Bay (ranging uniformly from 40 to 50%), and the balance from Wollaston Lake. Wollaston Post residents are assumed to take all of their catch from Wollaston Lake.

Fish from Wollaston Lake constitute an important staple in the diet of residents of the study area. Fishing camp residents may be expected to consume large quantities of fish (primarily lake trout) angled from the lake. Residents of the Post typically consume eight whitefish per capita each week. Annual consumption of fish, U_f , is set nominally at 100 kg per person, which is equivalent to 0.27 kg per day.

Nearly all of the fish consumed by local residents at Wollaston Post are from Wollaston Lake. Similarly, most of the angling based at Hidden Bay is practised in Wollaston Lake. Thus, the fraction of annual intake that is local fish, L_f , is close to one for Wollaston Post, and is assumed to be about 0.4 for Hidden Bay, corresponding to the fraction of the year when the fishing camp is active.

Parameter values used to calculate doses from fish ingestion are summarized in Table 4.13.

3. Annual Dose due to Water Intake

The doses received by the critical groups depends on concentrations of radionuclides in the water and on the amount of water consumed. The annual intake of water is 600 L/a, as defined by the ICRP (1975) for Reference Man. The concentrations of radionuclides in the water sources of the two reference receptors are those calculated in subroutine LAKE for Hidden Bay and Wollaston Lake. The fraction of annual intake that is from these sources, L_{wr} , is close to one for Wollaston Post, as this is a permanent (year-round) settlement, and about 0.4 for the Hidden Bay receptor, corresponding to the fraction of the year that the fishing camp is inhabited.

Table 4.13 summarizes parameters and statistical distributions used in the calculation of dose from water intake.

4.8.3 Inhalation Dose

1. Suspended Particulates

The inhalation dose received by residents of the two receptor locations depends on the atmospheric concentrations of radionuclides, the inhalation rate, and the fraction of the year spent at the receptor location. The inhalation rate, U_a , of $8,400 \text{ m}^3/\text{a}$ given by the ICRP (1975) for Reference Man is applied to both receptor locations. The occupancy factor, OF, is close to one for Wollaston Post residents, and about 0.4 for the seasonal residents of Hidden Bay. Atmospheric concentrations of particulate radionuclides at the two receptors are calculated by the AIRDIS subroutine.

Table 4.13 summarizes parameters and their distributions used in calculating dose due to inhalation of particulates.

2. Radon and Daughters

The inhalation dose from radon at the two receptor locations depends on the atmospheric radon concentration, on the equilibrium factor between radon and its short-lived daughters, in the fraction of time spent indoors at the receptor location, and on the dose conversion factor selected for inhalation, as described in SENES (1986).

As noted in the Phase III report (SENES, 1986), the equilibrium factor, F , is customarily selected rather than calculated due to the complexity of removal mechanisms for radon daughters. Here, we assume that F has a triangular distribution with a mode of 0.5. This average value is about the same as average values reported for radon in dwellings by UNSCEAR (1982).

In the Phase II study and in the BEAK (1986) non-pyritic demonstration of the Phase II UTAP model, a factor of 0.05 Sv/4.8 WLM was used to convert radon daughter exposure. As noted in the Phase III report SENES (1986), this factor was derived for occupational exposures, and a factor of 5×10^{-3} Sv/WLM has been suggested for non-occupational exposures due to lower breathing rates for the public compared to workers. For the two receptors considered, inhabitants are assumed to both reside and work at the receptor location, thus a conversion factor between these two values is appropriate for this application. The conversion factor used here is 0.007 Sv/WLM.

The indoor occupancy factor, $INOC_r$, is assumed to vary around a nominal value of 0.75 for $r = 2$ and 0.6 for $r = 1$.

The conversion between exposure to $1 \text{ Bq} \cdot \text{m}^{-3}$ of radon and annual dose is calculated in the DOSEIN subroutine by:

$$\begin{aligned} & INOC_r \times OF \times 1 \text{ Bq} \cdot \text{m}^{-3} \times 10^{-3} \text{ m}^3 \cdot \text{L}^{-1} \times F \\ & \times WL / (3.7 \text{ Bq} \cdot \text{L}^{-1}) \times 8,760 \text{ h} \cdot \text{a}^{-1} \times \text{WLM} / (WL \times 170 \text{ h}) \\ & \times 0.007 \text{ Sv/WLM} \end{aligned}$$

$$= INOC_r \times OF \times F \times 9.75 \times 10^{-5} \text{ Sv} \cdot \text{a}^{-1}$$

Parameter values and distributions used in the calculation of dose in the RADON subroutine are given in Table 4.13.

4.8 Calibration of Environmental Pathways

Model calibration is the selection of the frequency distribution of parameter values to achieve agreement between code calculations and observed data, while model validation is a comparison of the model's calculations with observations for a data set which is independent of any data sets used in the calibration. Model calibration may involve use of measured values from the laboratory or field, or comparing the model's predictions with observations and tuning the parameter values until predictions agree with observations.

The parameter values used for the model have been given previously in Tables 4.2 to 4.13. The sources of the data are explained in the text. All parameters were derived essentially from the literature, except for fish bioconcentration factors which were assessed in this project and radionuclide adsorption constants which were also measured in this project.

To evaluate the calibration described above, a comparison between model predictions and observations can only be made for one environment - the radionuclide activity in groundwater seepage from the toe of the dams. The calculated activity in all other environments (air, surface water, fish) cannot be assessed because sources other than the tailings influence the observed radionuclide activity in these environments.

The comparison between model predictions and observations is presented in Figures 4.8.1 to 4.8.6 for uranium, Th-230, Ra-226, Pb-210, calcium and sulphate for the south dam, and in Figures 4.8.7 to 4.8.12 for the same substances, respectively, in the north dam. The values used for the calibration are given in Table 4.2. The main differences between calibrated and measured parameter values are values for the linear adsorption coefficients, K_d . They are:

Figure 4.8.1

CONCENTRATION vs. TIME
FOR URANIUM
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

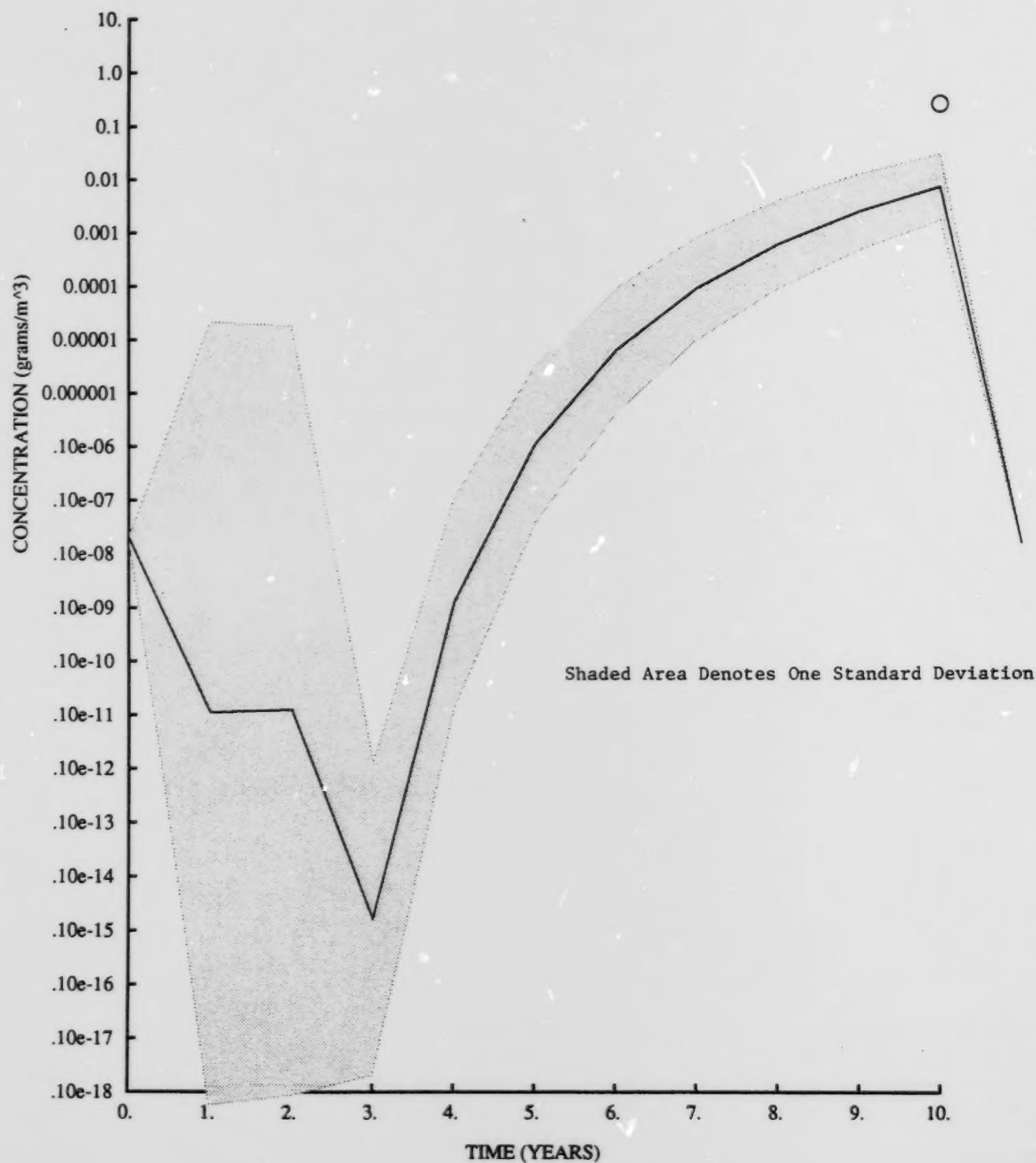


Figure 4.8.2

CONCENTRATION vs. TIME
FOR TH-230
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

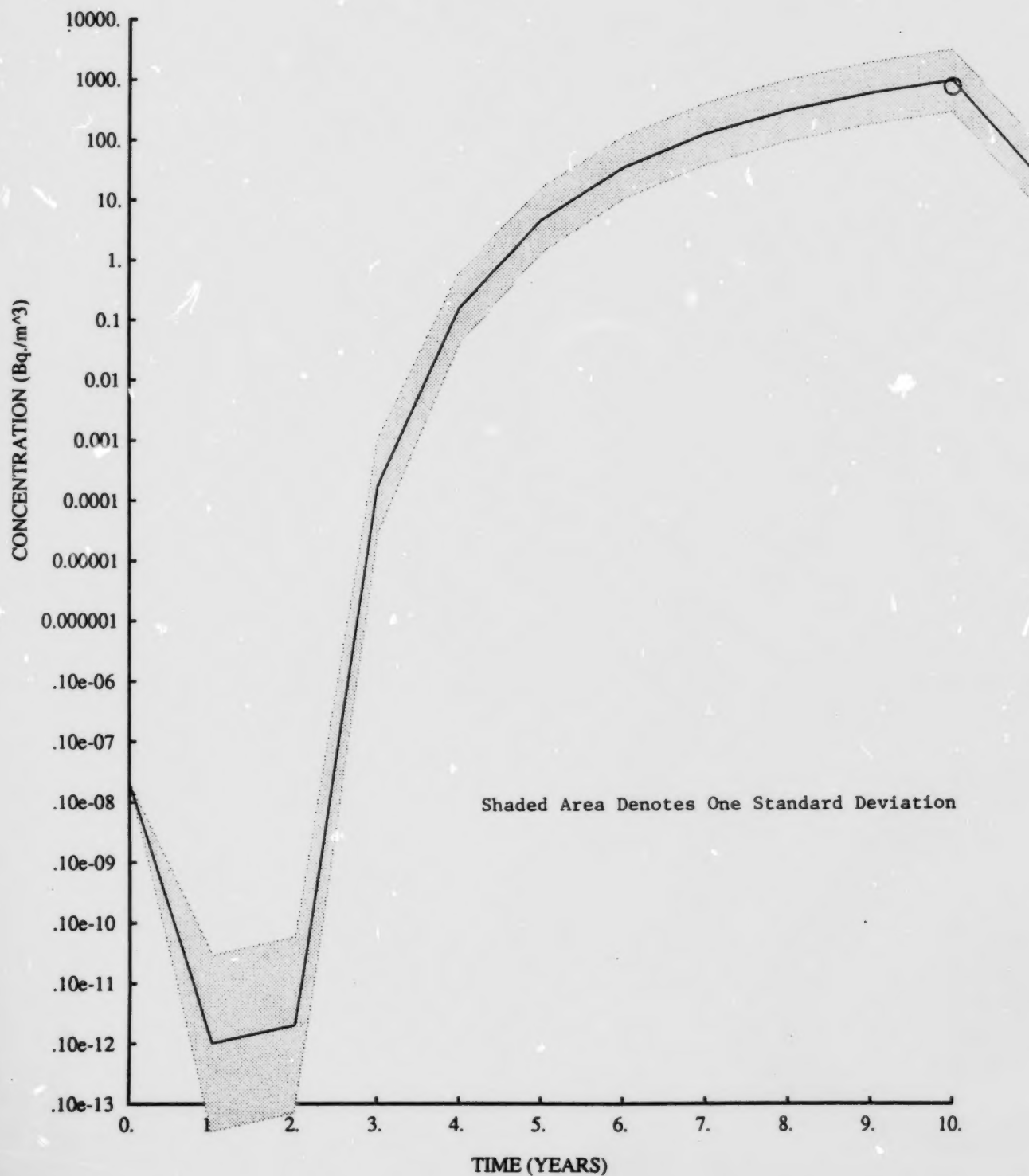


Figure 4.8.3

CONCENTRATION vs. TIME
FOR RA-226
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

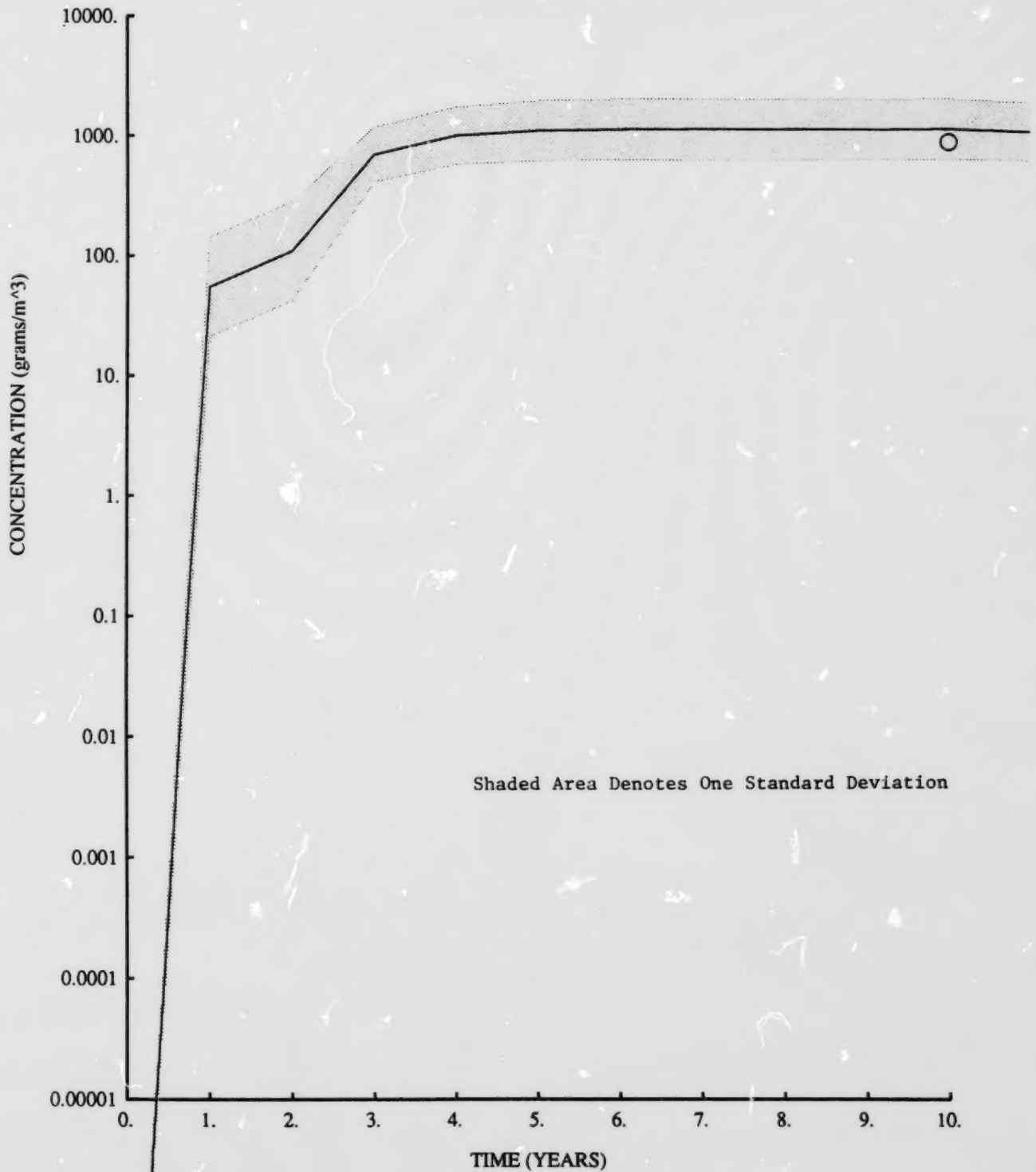


Figure 4.8.4

CONCENTRATION vs. TIME
FOR PB-210
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

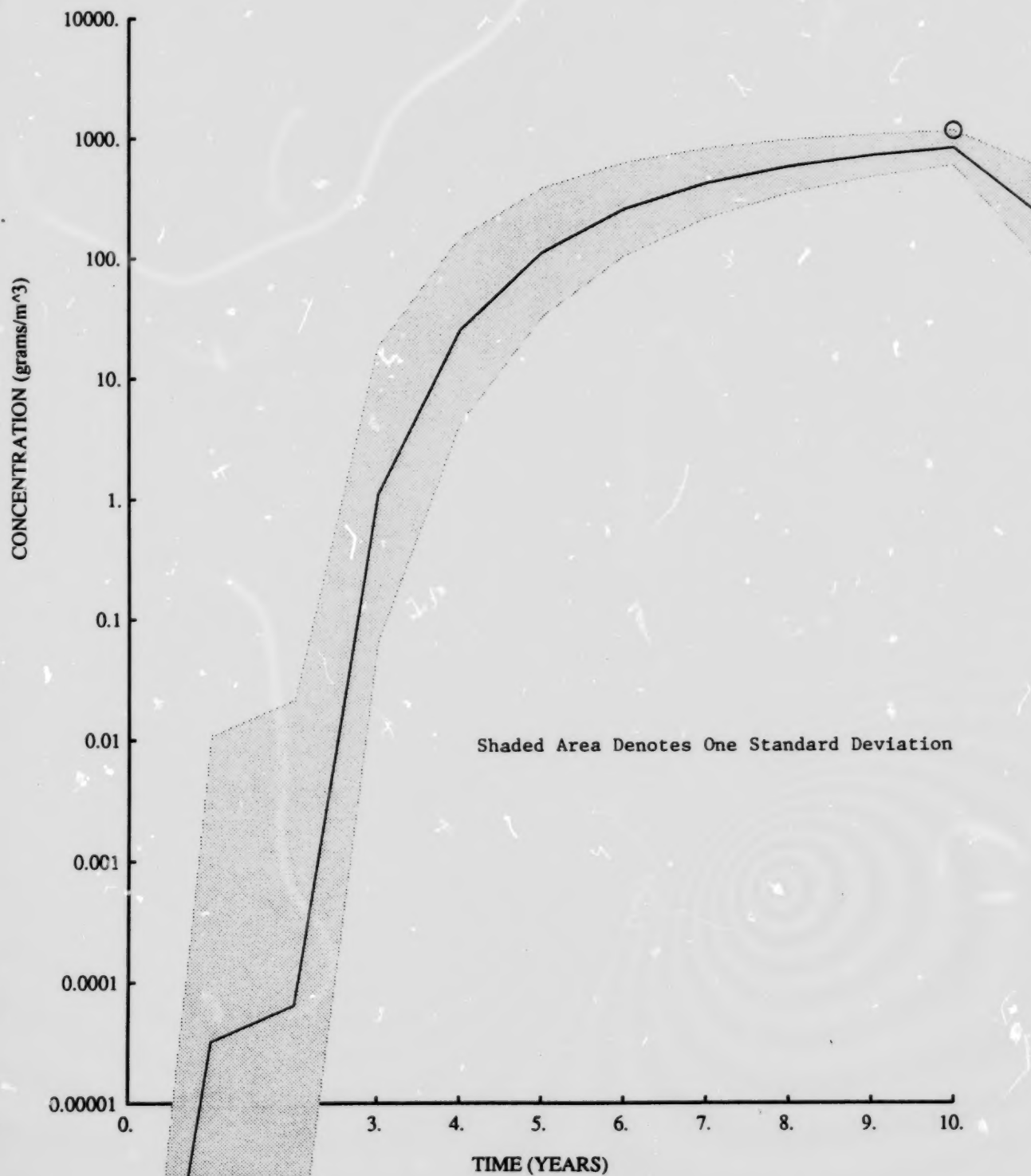


Figure 4.8.5

CONCENTRATION vs. TIME
FOR CALCIUM
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

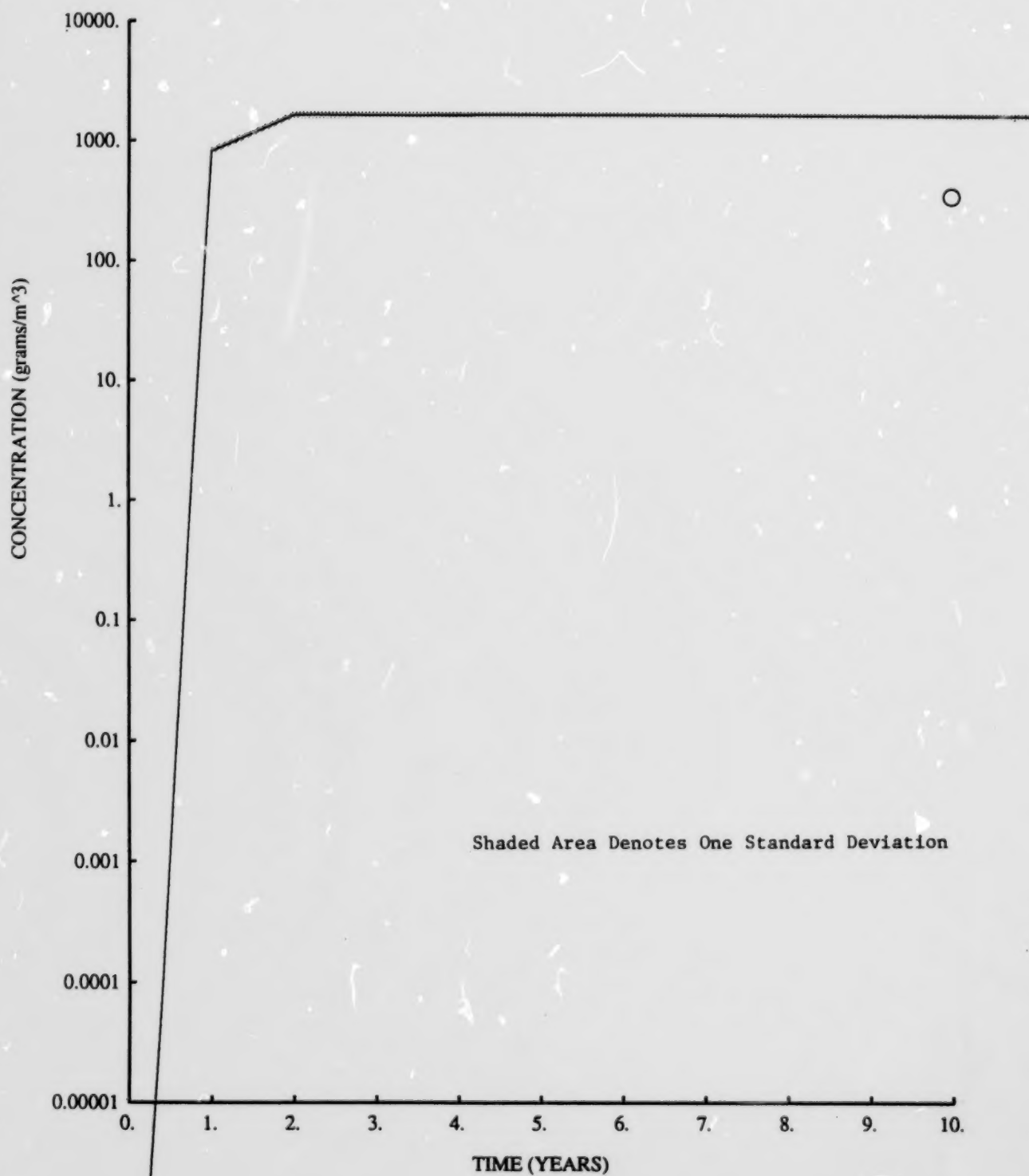


Figure 4.8.6

CONCENTRATION vs. TIME
FOR SULPHATE
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

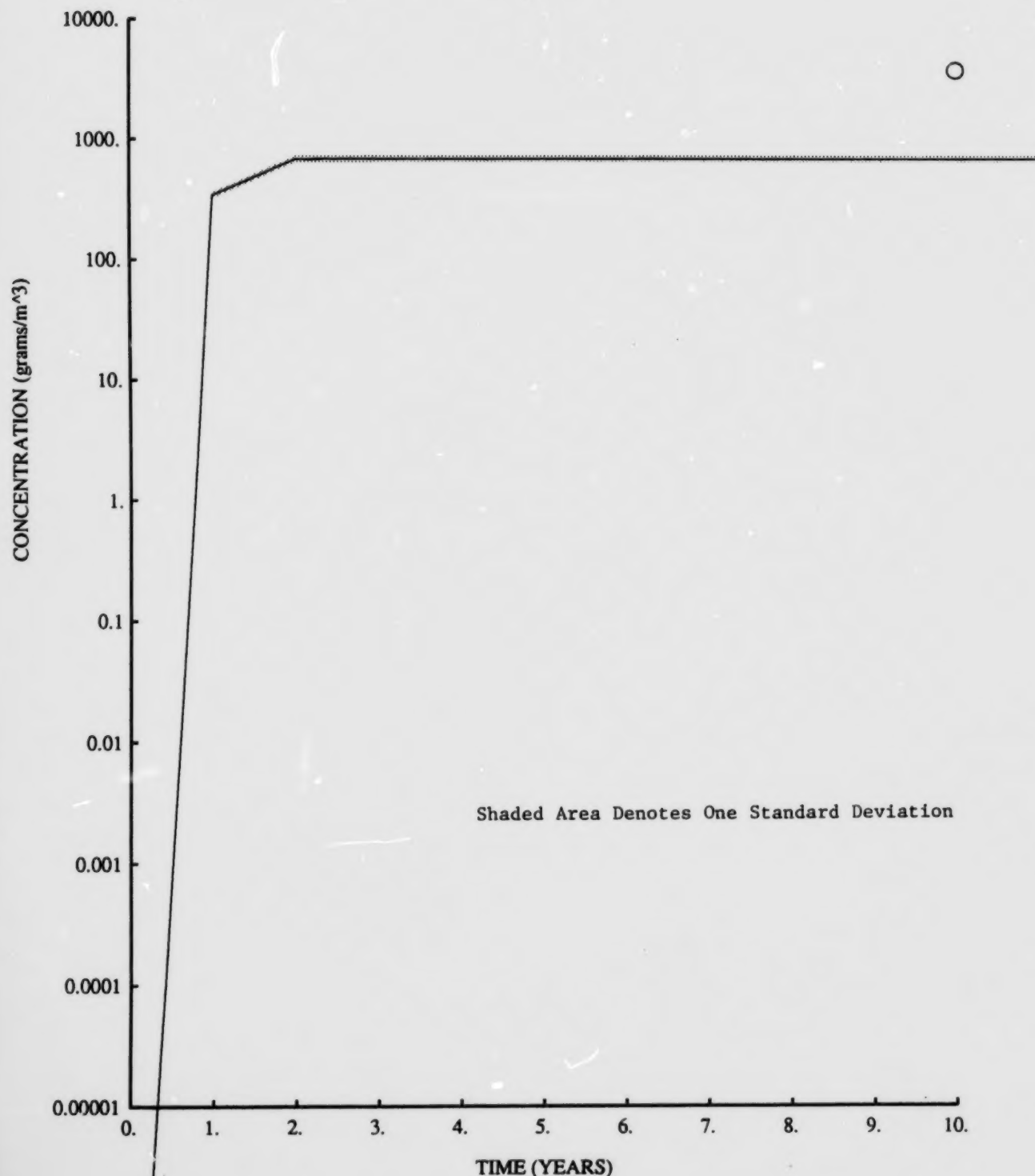


Figure 4.8.7

CONCENTRATION vs. TIME
FOR URANIUM
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

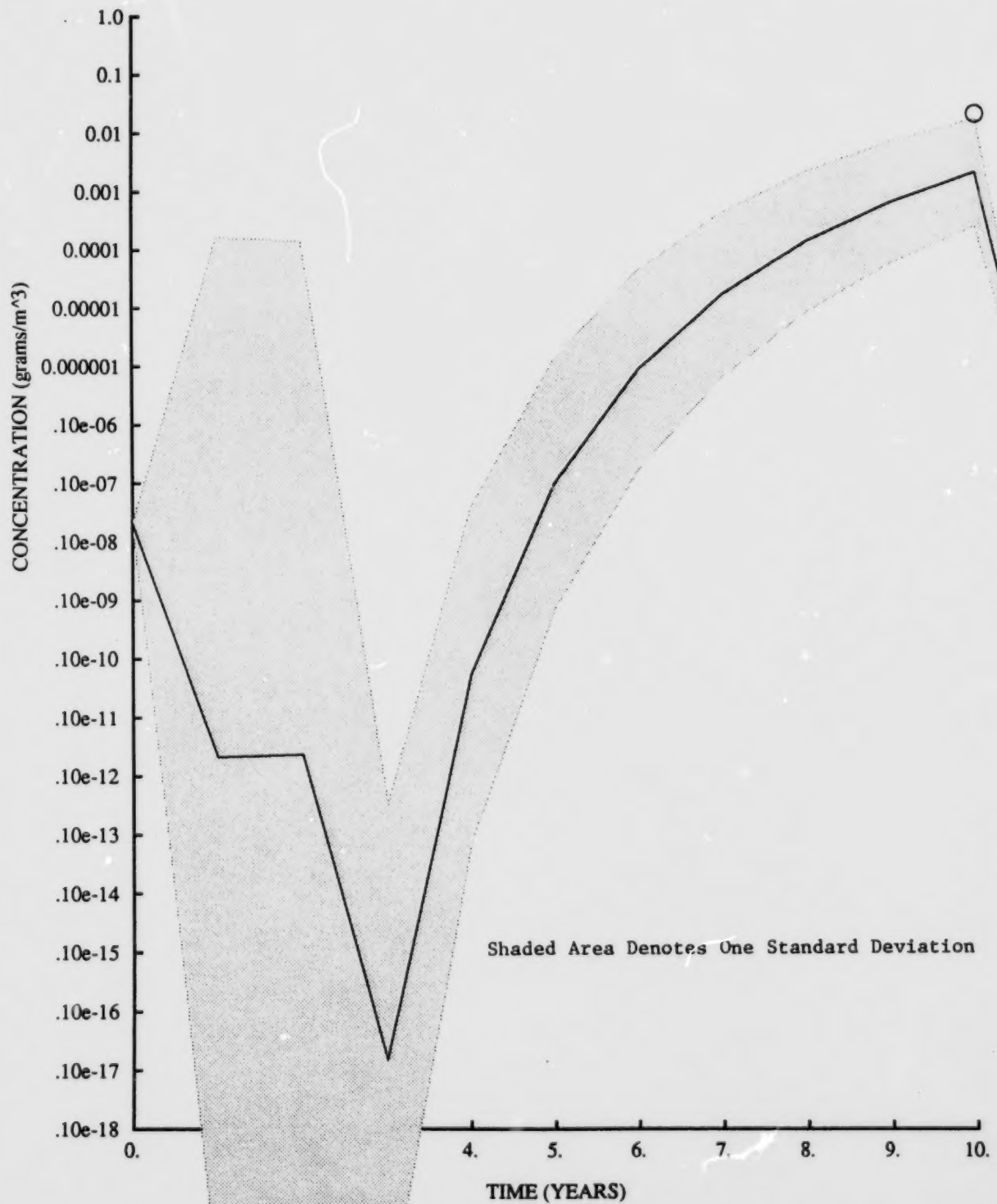


Figure 4.8.8

CONCENTRATION vs. TIME
FOR TH-230
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

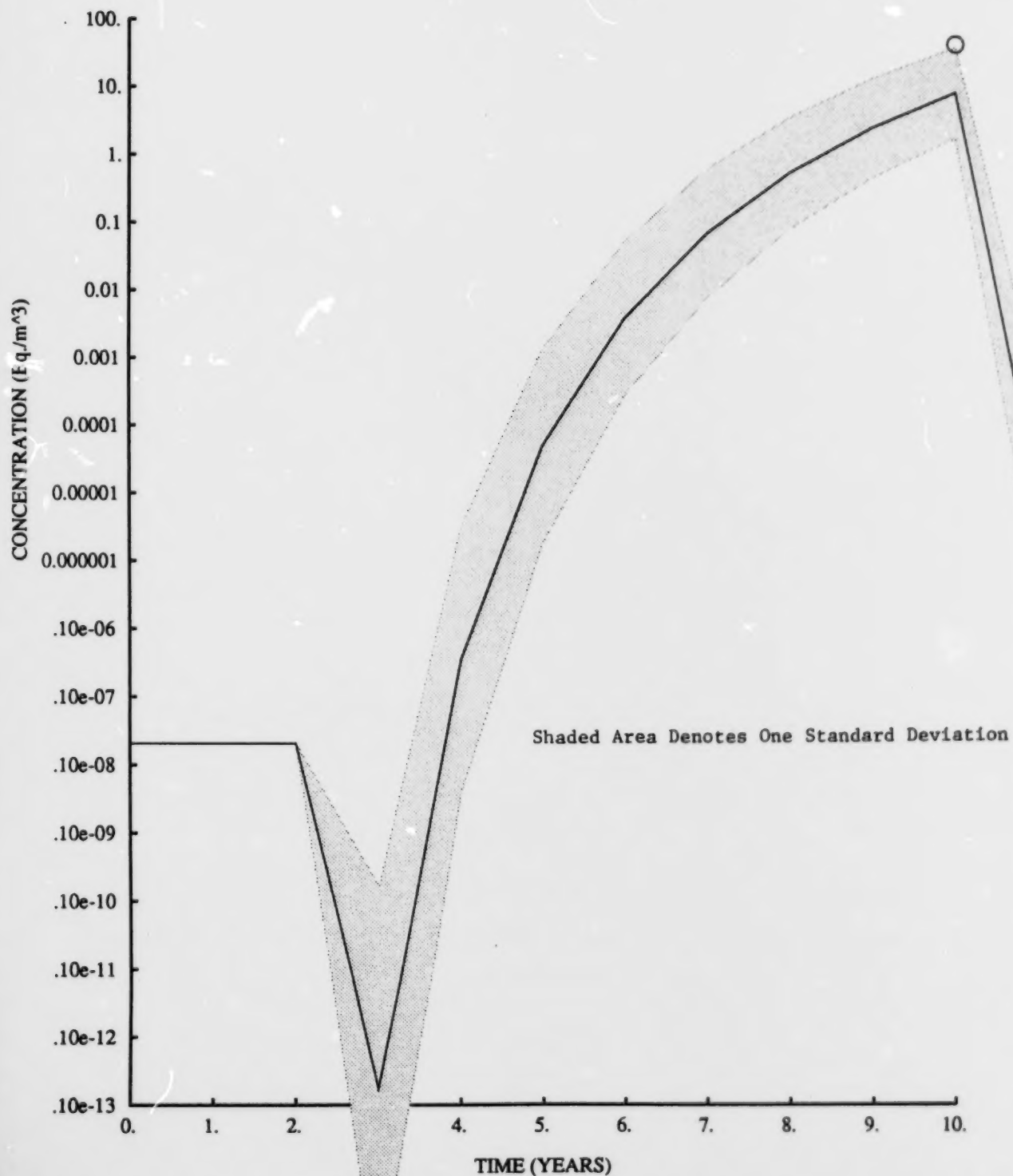


Figure 4.8.9

CONCENTRATION vs. TIME
FOR RA-226
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

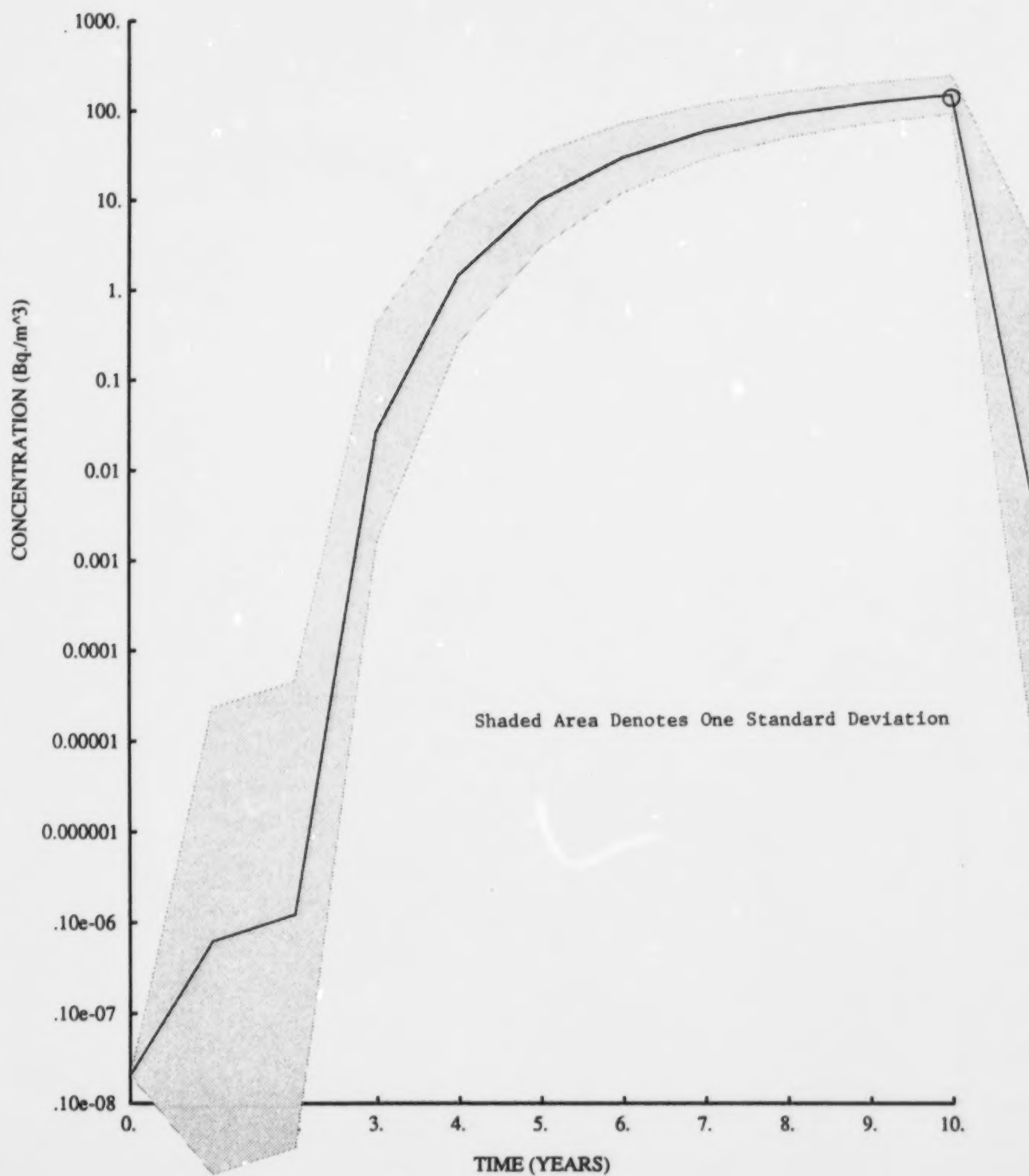


Figure 4.10

CONCENTRATION vs. TIME
FOR PB-210
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

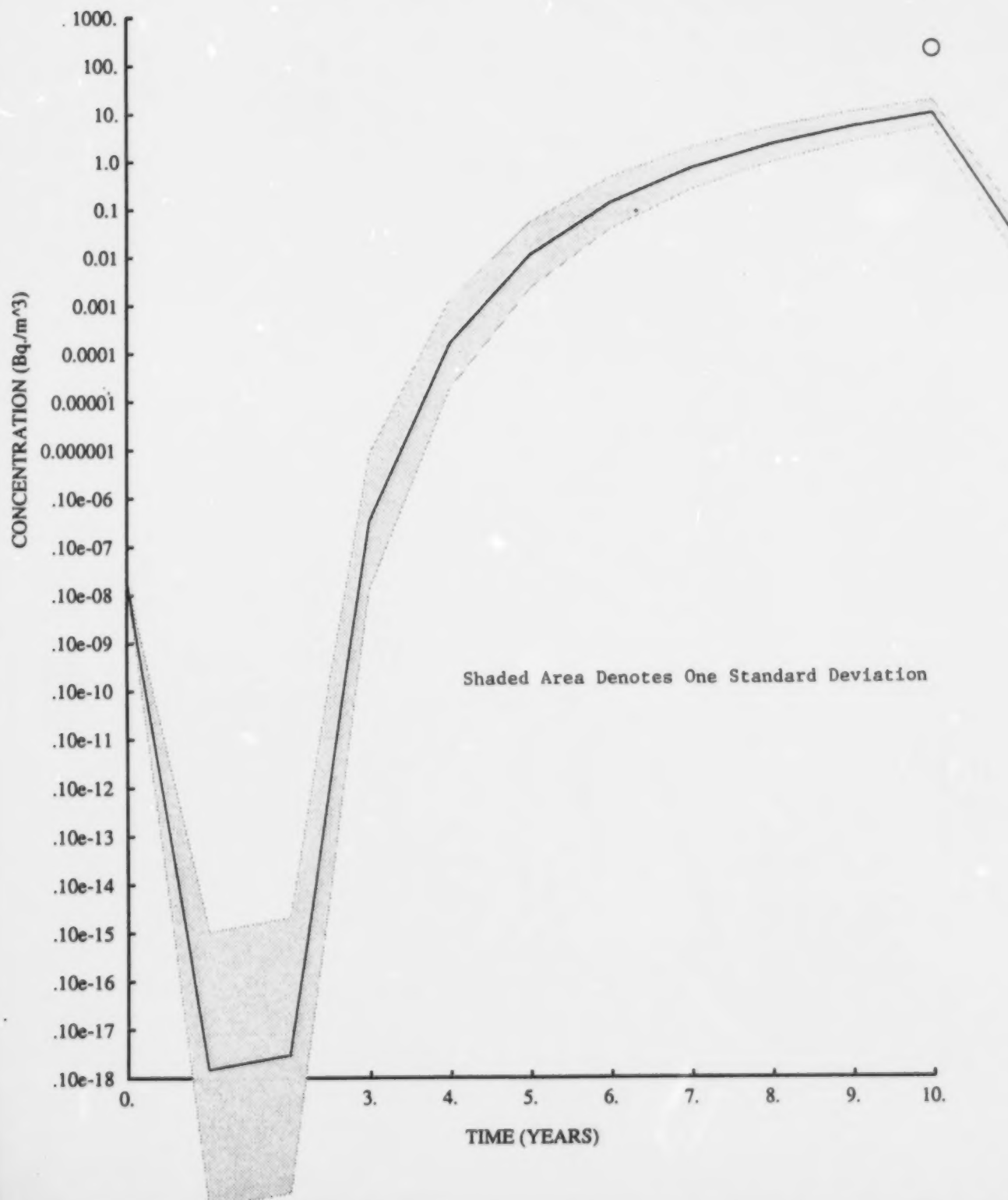


Figure 4.8.11

CONCENTRATION vs. TIME
FOR CALCIUM
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

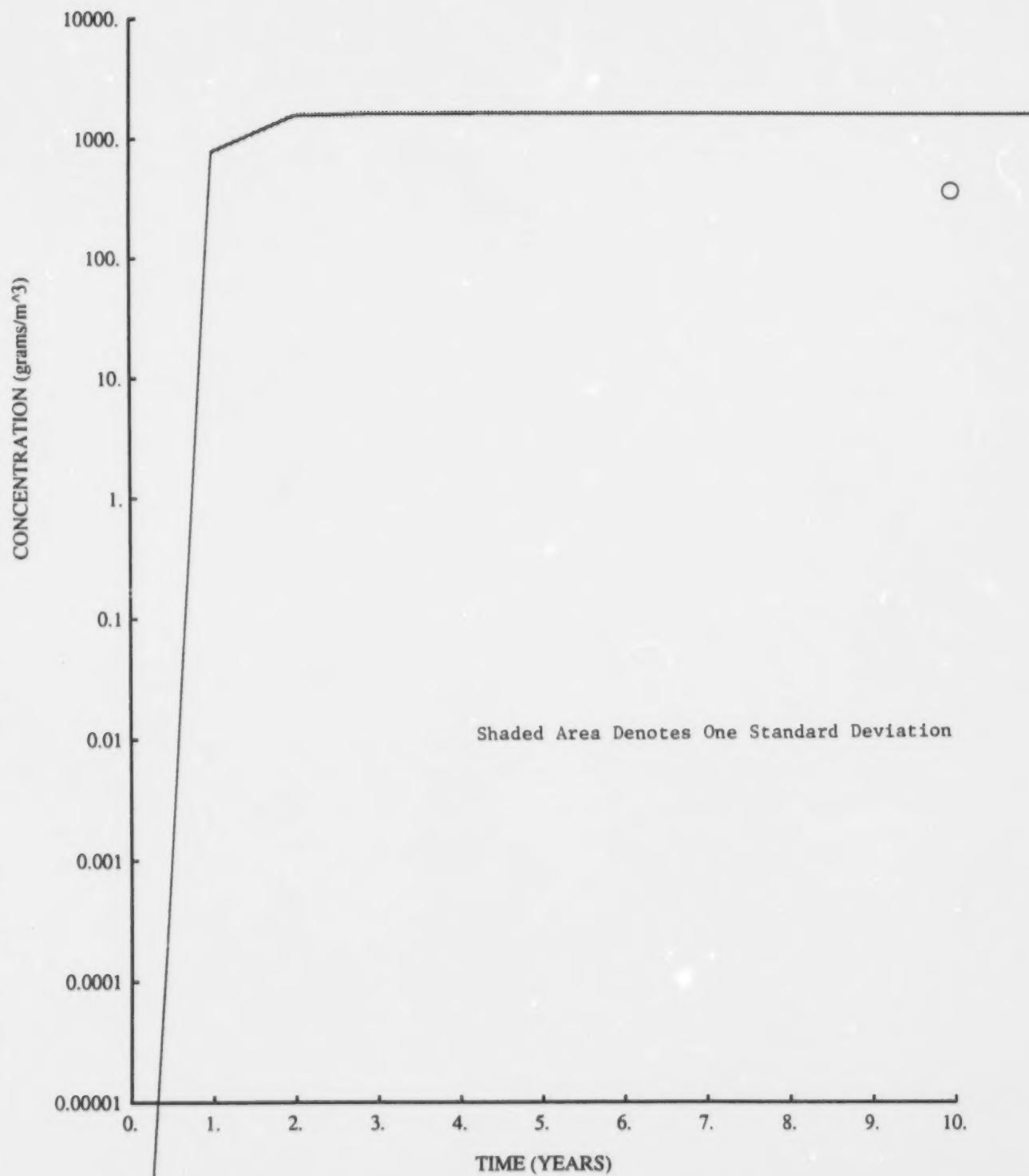
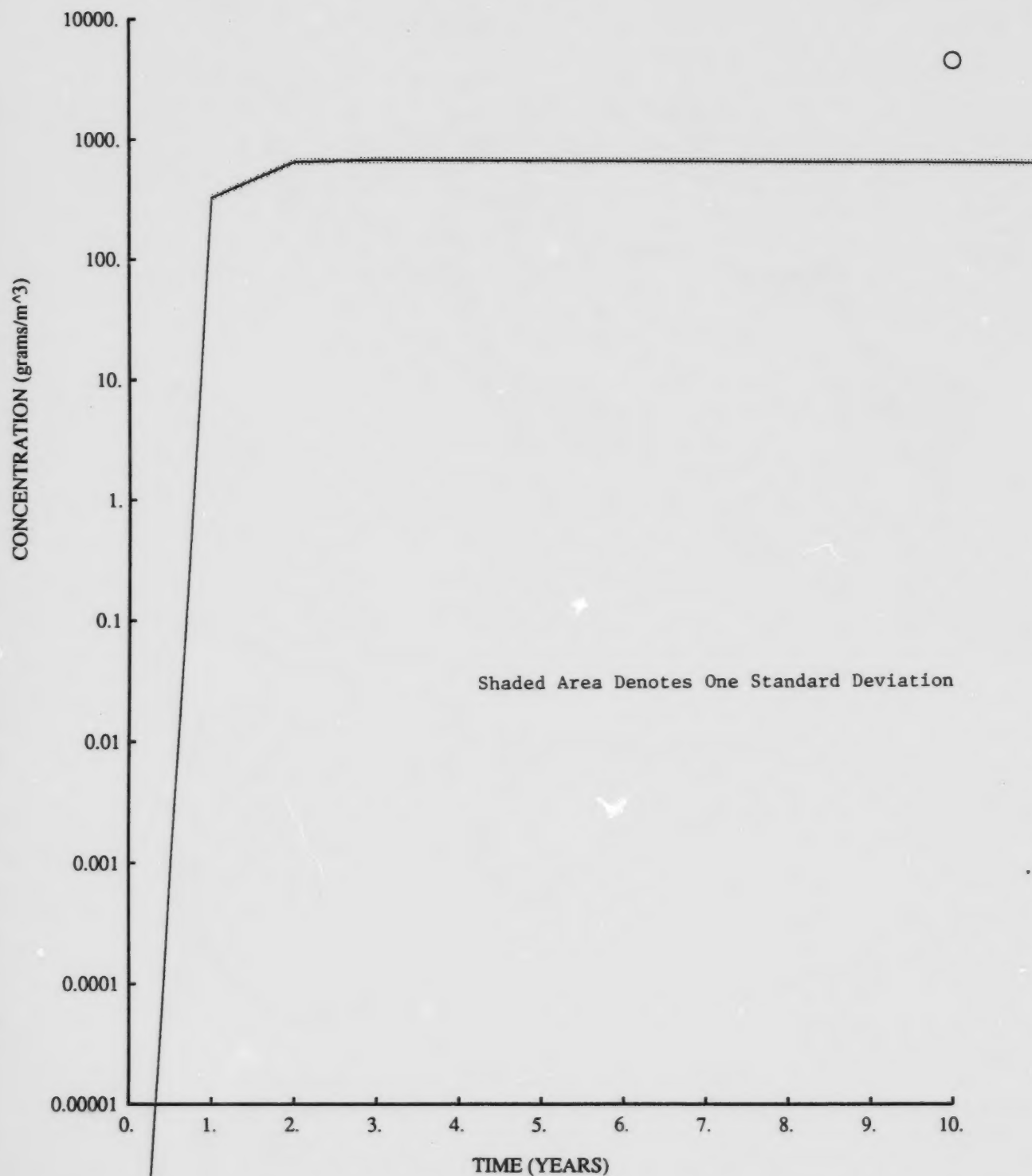


Figure 4.8.12

CONCENTRATION vs. TIME
FOR SULPHATE
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS



Substance	Nominal Value for Glacial Till from Experiment (Table 4.10)	Nominal Value Determined from Calibration (Table 4.2)
	(m ³ /kg)	(m ³ /kg)
U	0.1	0.01
Th-230	1.8	0.012
Ra-226	8.6	0.007
Pb-210	9.3	0.005
calcium	-	0
SO ₄	-	0

These adsorption constants are approximately two orders of magnitude lower for Th-230 than those measured experimentally on glacial tills for the area. The constants for Ra-226 and Pb-210 are approximately three orders of magnitude lower than those measured on the glacial tills for 10^{-3} molar sodium bicarbonate solutions. The values given for the calibration (Table 4.2) were determined after initially starting with the values of Table 4.10 and changing them until a reasonable agreement was obtained between predicted values and measured concentrations.

The adsorption constants measured should give reasonable results. The tills used as substrate for the adsorption experiments should be representative of dam materials because the tills were obtained from burrow pits from which dam materials were obtained. Also, the measurements show reasonable consistency between duplicates.

An explanation for the differences between experimental measurements and calibrated values is found in solution chemistry and competitive adsorption. The experiments (BEAK, 1987) show that there is an order of magnitude decrease in the adsorption constant for Ra-226 when the solution strength increases from 10^{-3} M NaHCO₃ to 10^{-1} M NaHCO₃. This is caused by competitive adsorption between sodium and Ra-226 for the same ion exchange sites - a higher concentration of sodium ions in solution compared to a constant number of radium-226 ions result in sites occupied by Ra-226 at lower solution strength to be occupied by Na ions at higher solution strength. This lowers the amount of Ra-226 adsorbed at higher ionic strength and hence decreased K_D for increasing ionic strength.

A further explanation for differences between measured and calibrated values is the nature of materials in the dams. The south dam is partially composed of recycled tailings. Dissolution of Ra-226 and Pb-210 from within the dam would increase the flux of these radionuclides from the dam and reduce the "apparent" adsorption constant.

5.0 CALCULATIONS AND SENSITIVITY ANALYSIS

5.1 Model Calculations of Dose Rate

This section gives dose calculations for the base case and for the different management scenarios. The results are given in groups of four. The groups are as follows:

- o Figure 5.1: Scenario I (Base Case)
- o Figure 5.2: Scenario II (0.6 m till cover)
- o Figure 5.3: Scenario III (0.6 m bentonite clay cover)
- o Figure 5.4: Scenario IV (waste rock cover)

Within each group, six plots are given. For the Figure 5.1 group, for example, the following figures are given:

- o Figure 5.1.1: Total Dose with Associated Confidence Limits, 2 Receptors
- o Figure 5.1.2: Frequency Histograms for Total Dose, 2 Receptors
- o Figure 5.1.3: Dose by Pathway for Hidden Bay Receptor
- o Figure 5.1.4: Dose by Pathway for Wollaston Lake Receptor
- o Figure 5.1.5: Dose by Radionuclide for Hidden Bay Receptor
- o Figure 5.1.6: Dose by Radionuclide for Wollaston Lake Receptor

The lake concentrations associated with the base case are given in Figure 5.5. They are analyzed in more depth in Appendix E.

For the base case, the total dose rate is of the order of 1 to 10 uSv/year for both receptors. For all three management cases, the total dose rate is similar in value to that for the base case. The dose rate to the Hidden Bay receptor is numerically slightly lower than that to the Wollaston Lake receptor (see histogram statistics for Wollaston Lake (Post) and Hidden Bay receptors).

The similarity of total dose rate results from the relative importance of radionuclides transported via aquatic and atmospheric pathways. The dose rate from the aquatic pathways is over an order of magnitude larger than from the atmospheric pathways

FIGURE 5.1.1a: TOTAL DOSE vs. TIME
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1,
GEOMETRIC MEAN OF 500 TRIALS

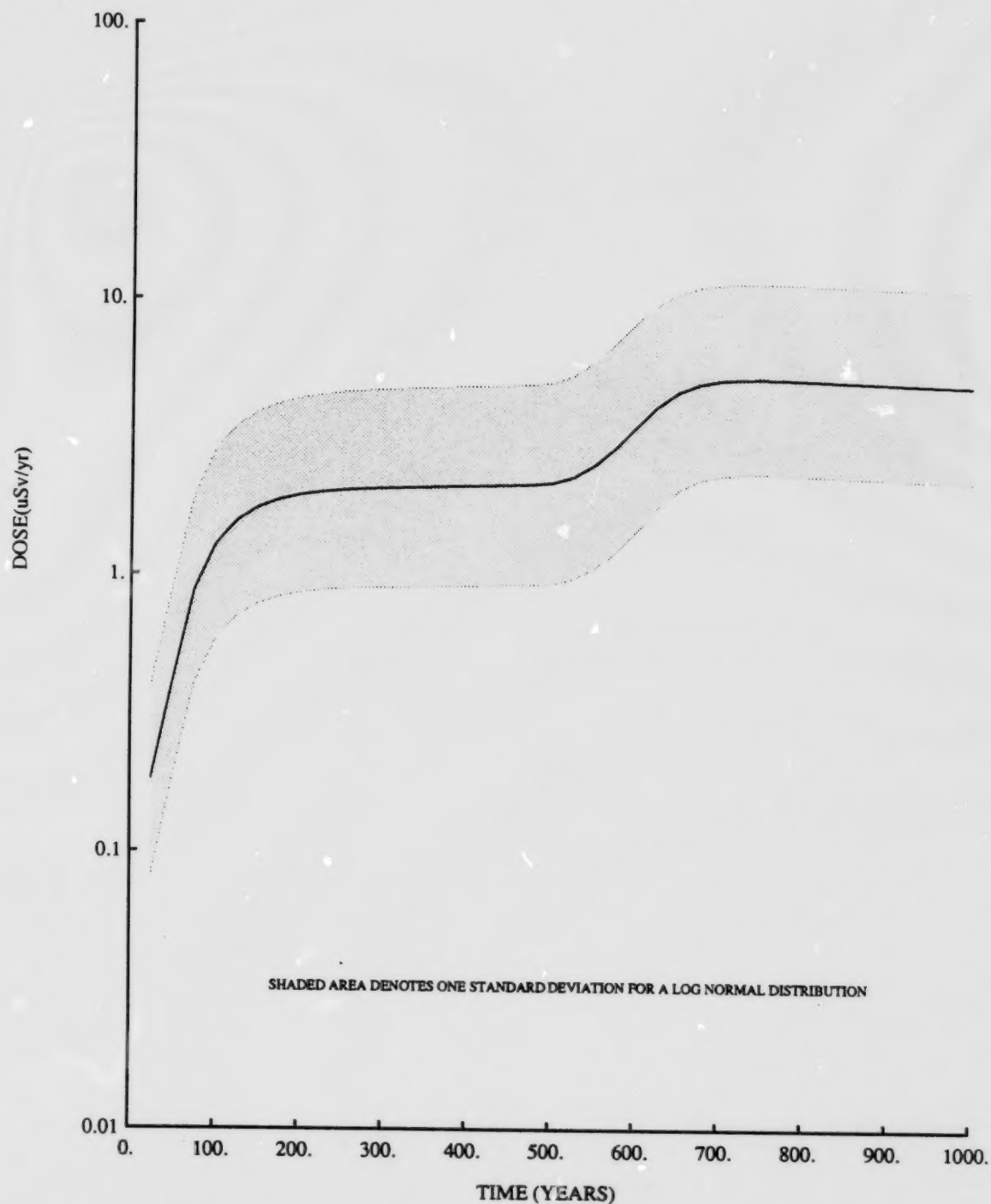
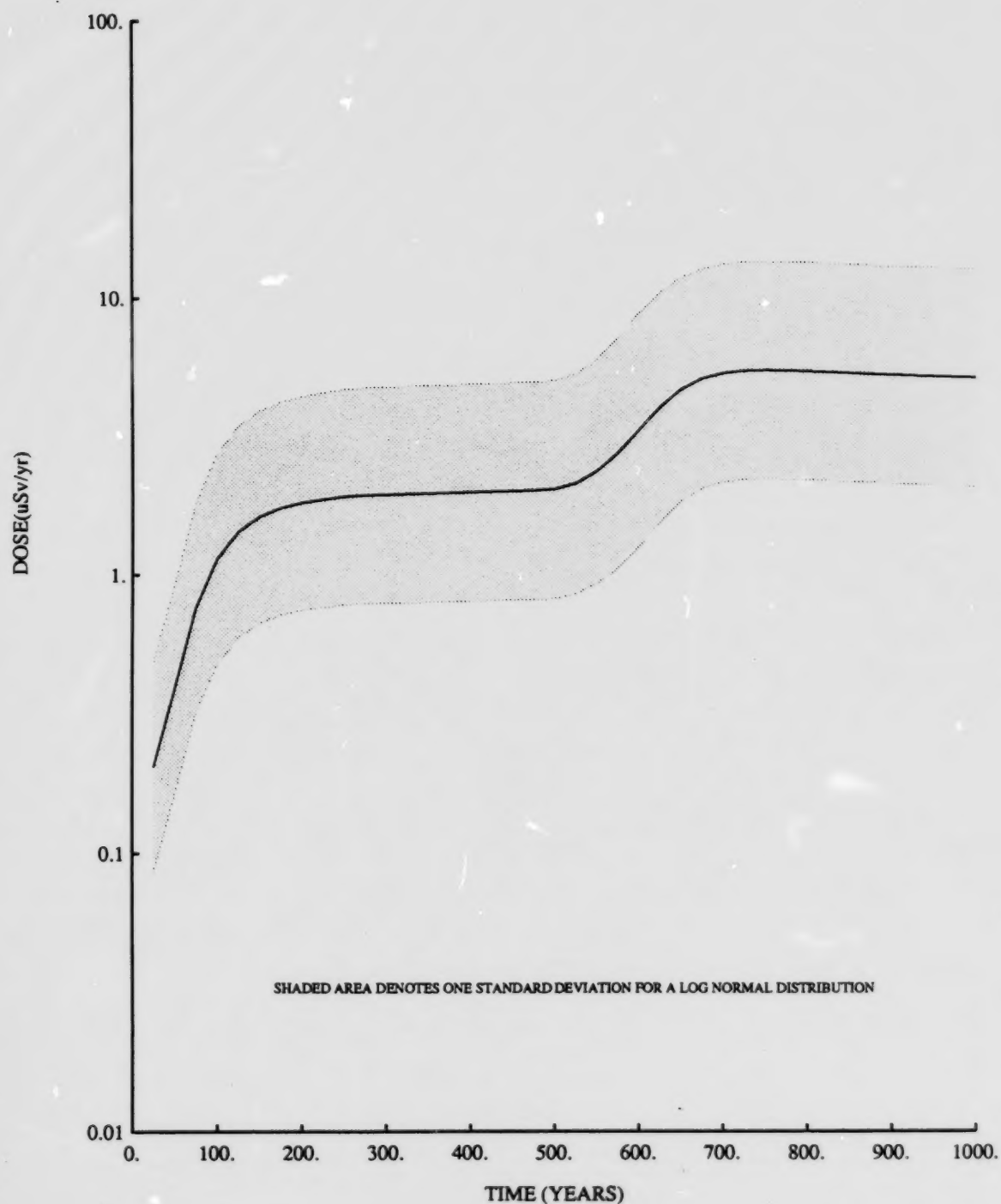
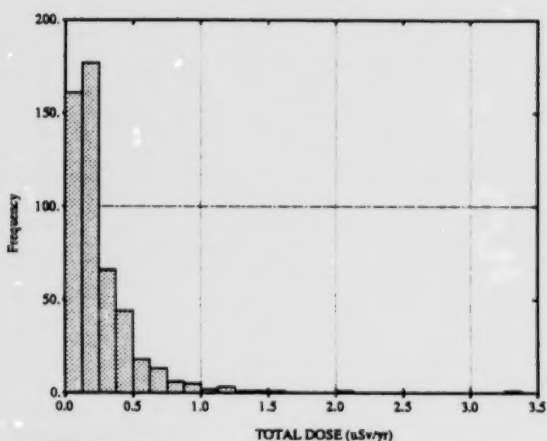


FIGURE 5.1.1b: TOTAL DOSE vs. TIME
AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1,
GEOMETRIC MEAN OF 500 TRIALS



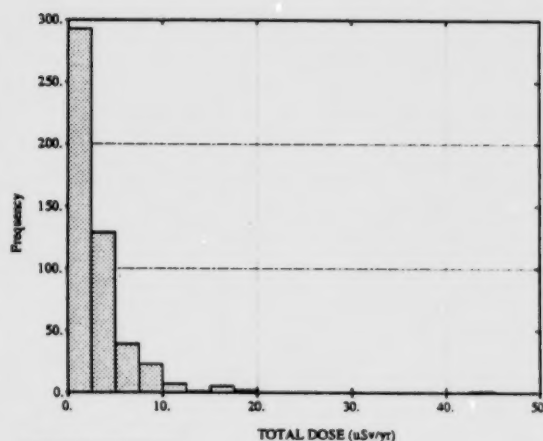
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.256
STANDARD DEVIATION = 0.270
GEOMETRIC MEAN = 0.183
GEOMETRIC STANDARD DEVIATION = 2.22
MINIMUM = 0.294e-01
MAXIMUM = 3.28

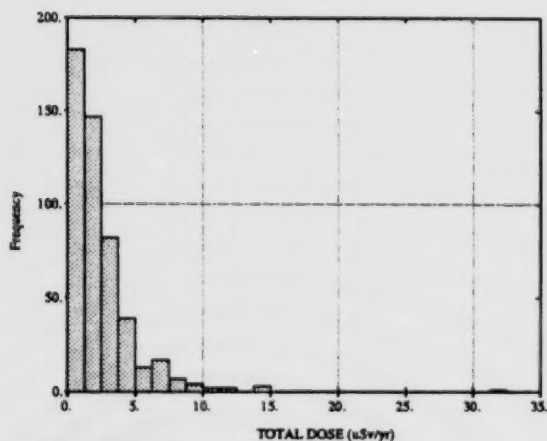
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1, AT T = 400



SUMMARY STATISTICS:

MEAN = 3.05
STANDARD DEVIATION = 3.34
GEOMETRIC MEAN = 2.12
GEOMETRIC STANDARD DEVIATION = 2.30
MINIMUM = 0.281
MAXIMUM = 42.7

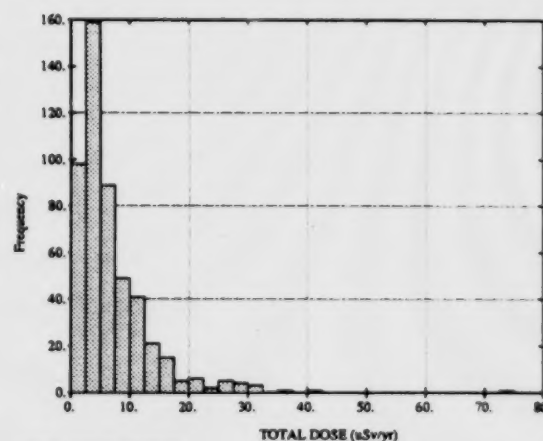
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.45
STANDARD DEVIATION = 2.51
GEOMETRIC MEAN = 1.75
GEOMETRIC STANDARD DEVIATION = 2.23
MINIMUM = 0.249
MAXIMUM = 31.4

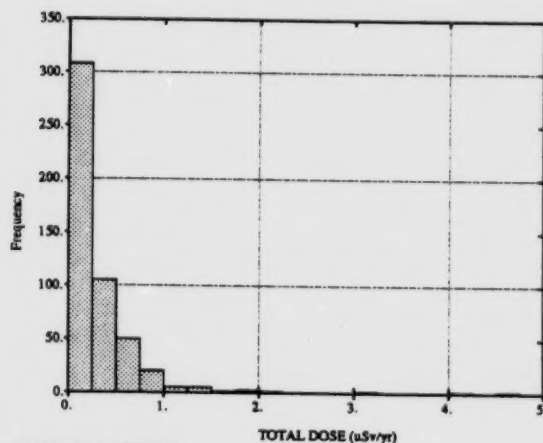
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1, AT T = 1000



SUMMARY STATISTICS:

MEAN = 6.95
STANDARD DEVIATION = 6.71
GEOMETRIC MEAN = 5.00
GEOMETRIC STANDARD DEVIATION = 2.22
MINIMUM = 0.643
MAXIMUM = 74.1

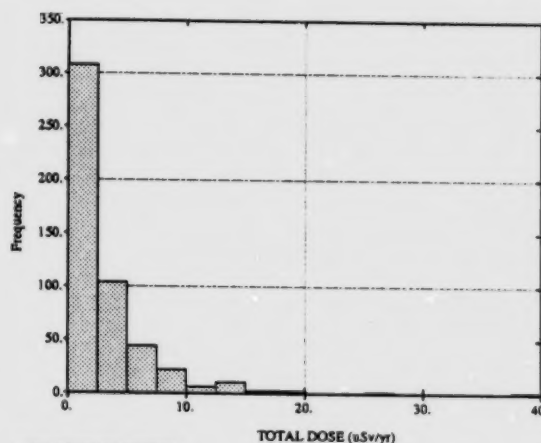
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 1, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.313
STANDARD DEVIATION = 0.407
GEOMETRIC MEAN = 0.205
GEOMETRIC STANDARD DEVIATION = 2.39
MINIMUM = 0.290e-01
MAXIMUM = 4.65

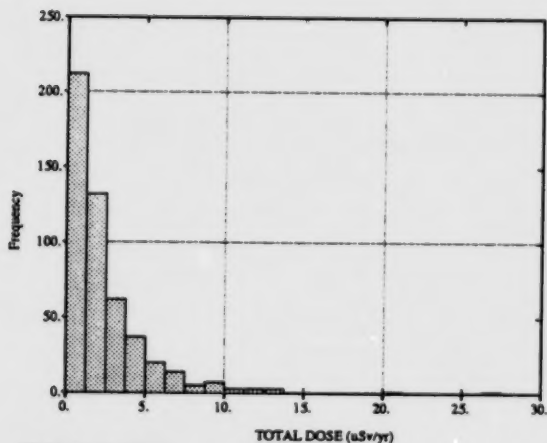
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 1, AT T = 400



SUMMARY STATISTICS:

MEAN = 3.08
STANDARD DEVIATION = 3.52
GEOMETRIC MEAN = 2.01
GEOMETRIC STANDARD DEVIATION = 2.47
MINIMUM = 0.293
MAXIMUM = 38.6

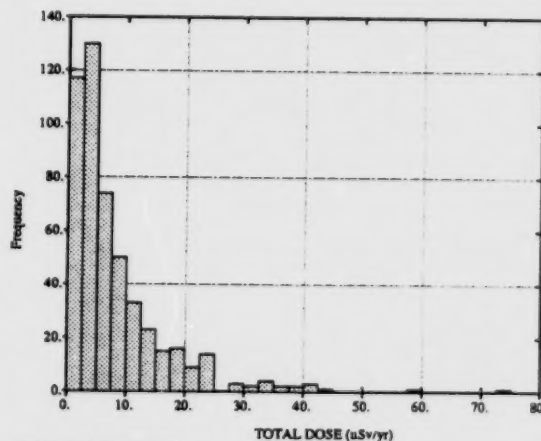
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 1, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.45
STANDARD DEVIATION = 2.67
GEOMETRIC MEAN = 1.63
GEOMETRIC STANDARD DEVIATION = 2.42
MINIMUM = 0.266
MAXIMUM = 26.7

HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 1, AT T = 1000



SUMMARY STATISTICS:

MEAN = 8.05
STANDARD DEVIATION = 8.53
GEOMETRIC MEAN = 5.29
GEOMETRIC STANDARD DEVIATION = 2.47
MINIMUM = 0.802
MAXIMUM = 73.5

FIGURE 5.1.3 : DOSE vs. TIME
FOR SCENARIO 1, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR



FIGURE 5.1.4 : DOSE vs. TIME
FOR SCENARIO 1, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

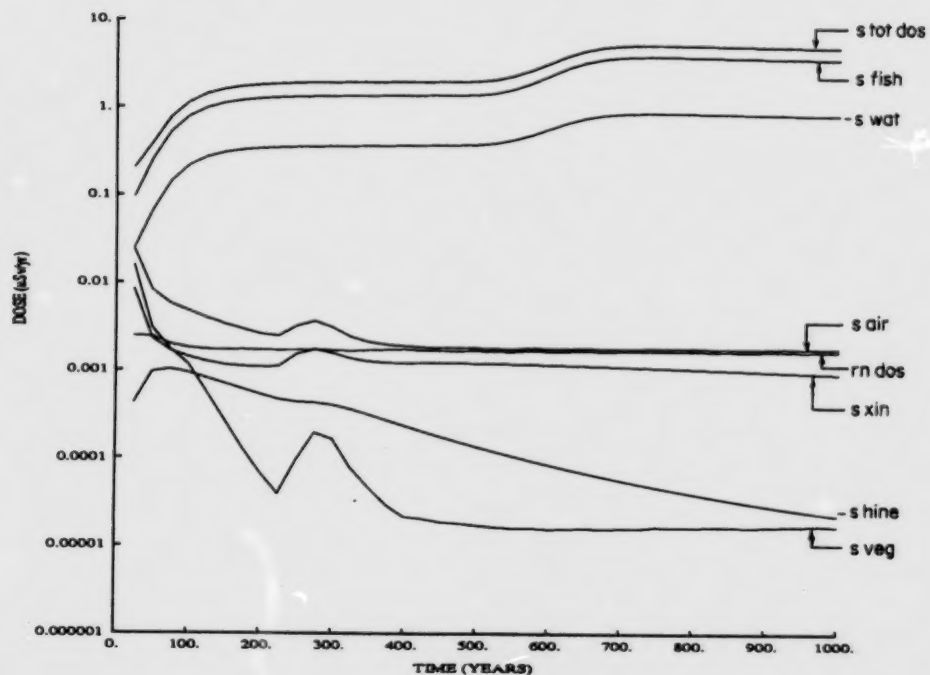


FIGURE 5.1.5 : DOSE vs. TIME
FOR SCENARIO 1, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

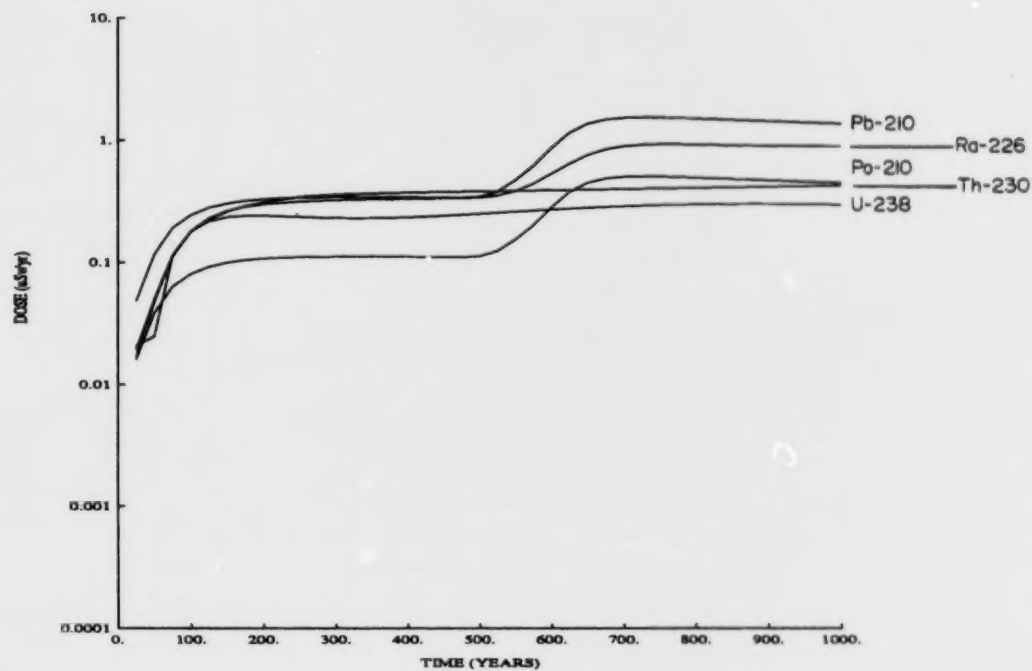


FIGURE 5.1.6 : DOSE vs. TIME
FOR SCENARIO 1, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

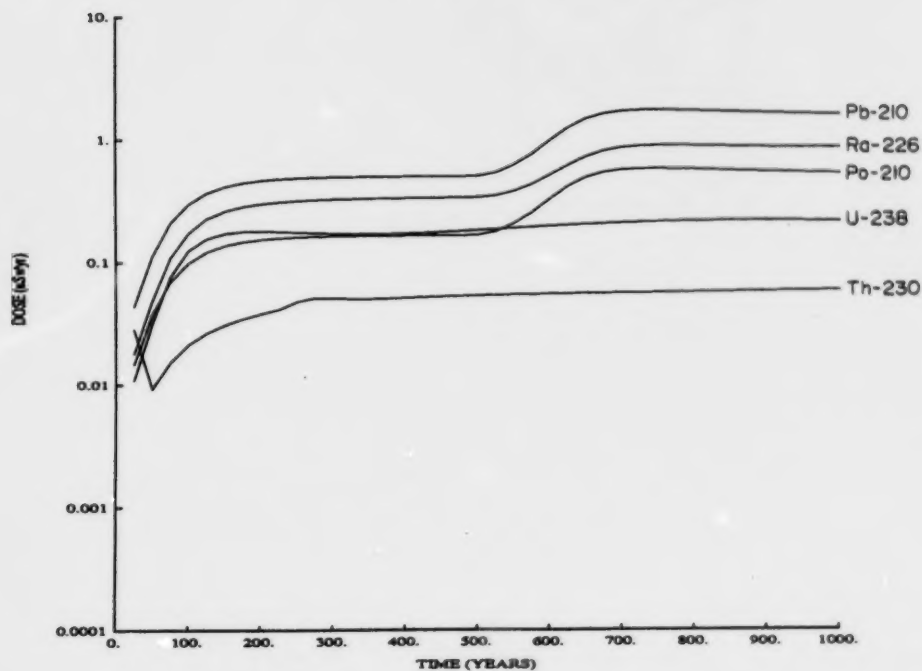


FIGURE 5.2.1a: TOTAL DOSE vs. TIME
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 2,
GEOMETRIC MEAN OF 500 TRIALS

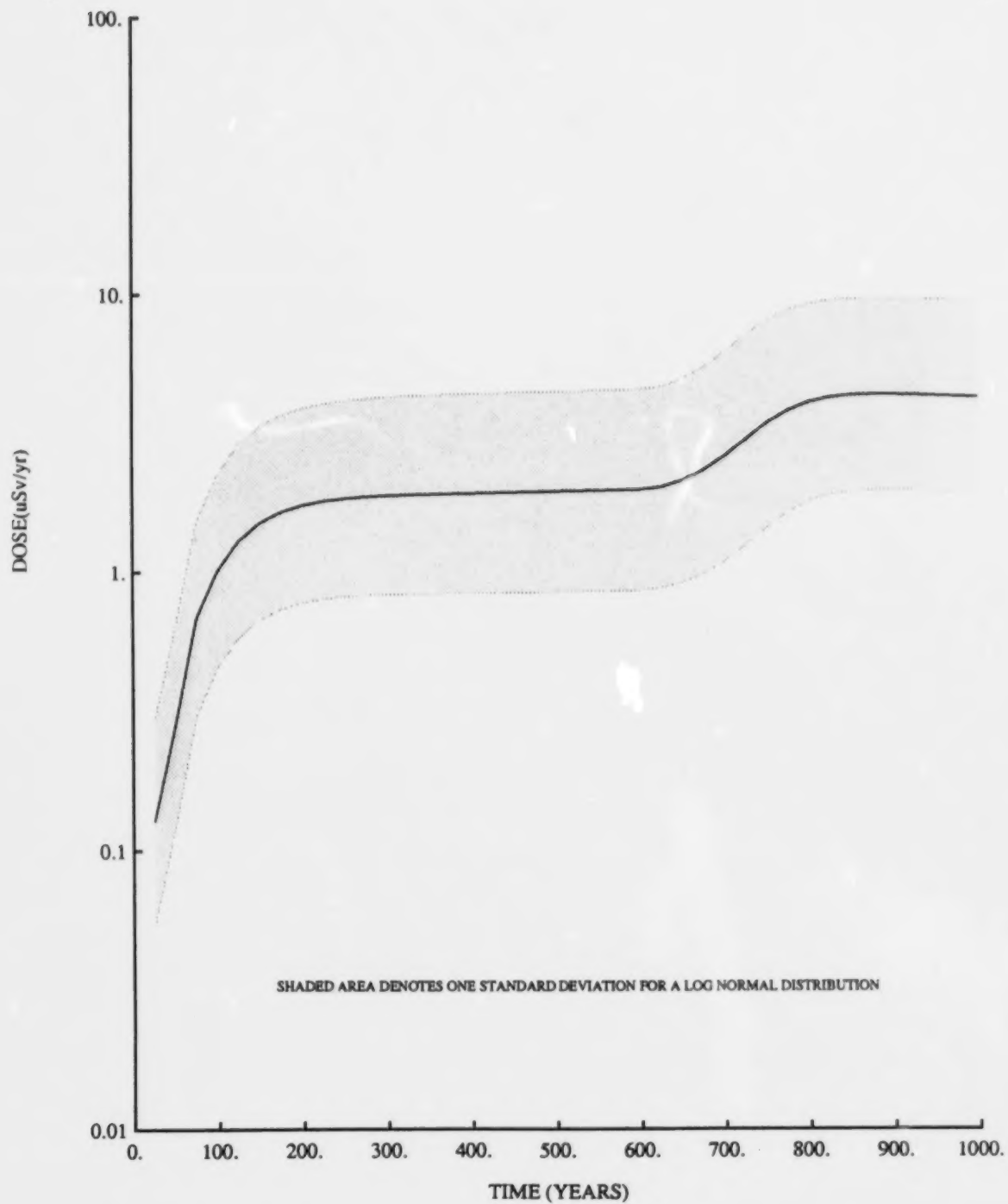
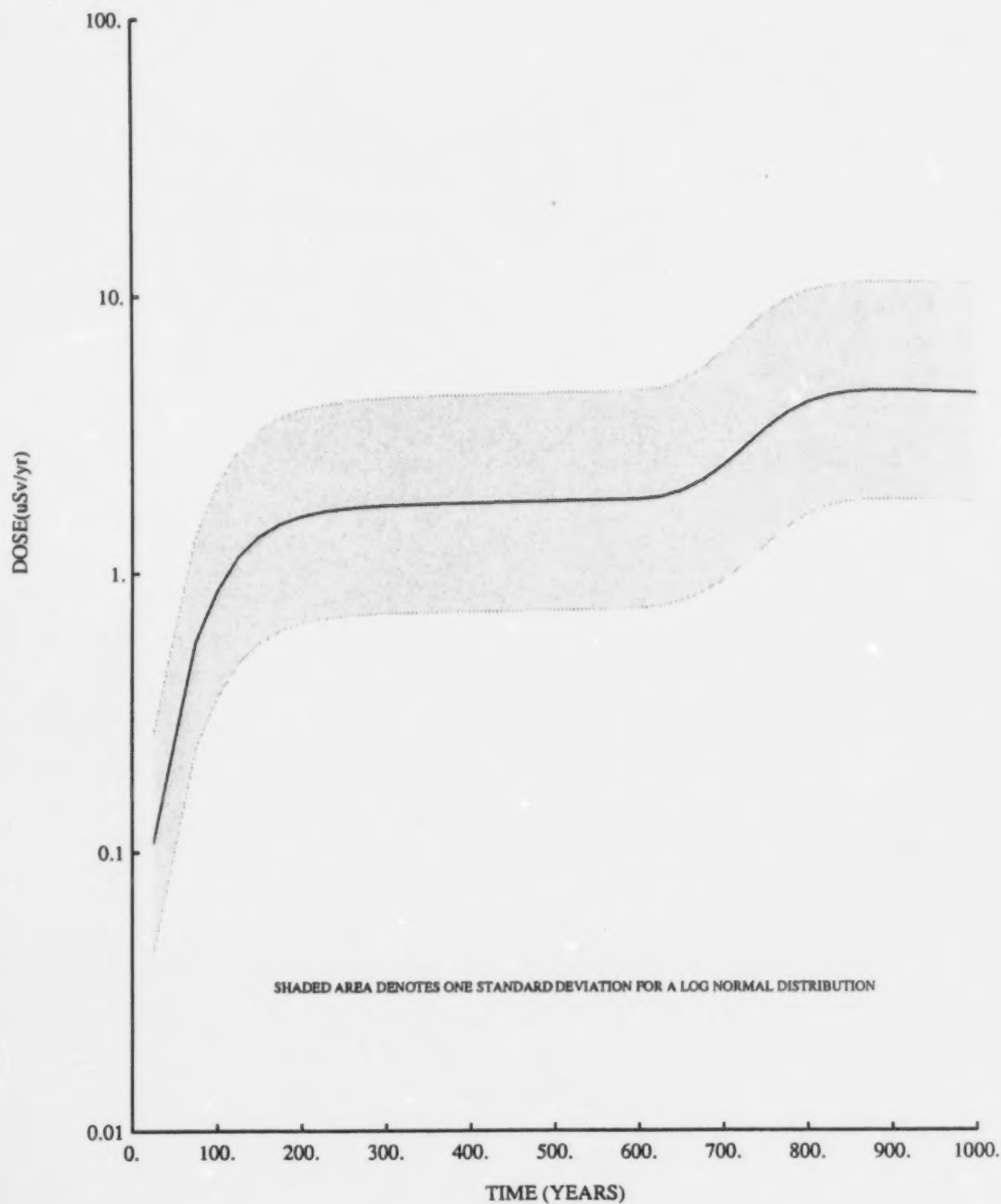
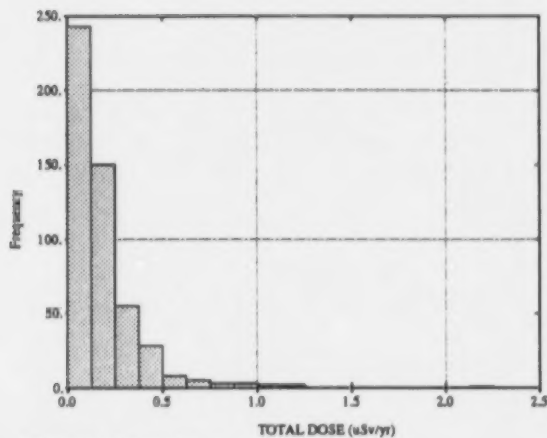


FIGURE 5.2.1b: TOTAL DOSE vs. TIME
AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 2,
GEOMETRIC MEAN OF 500 TRIALS



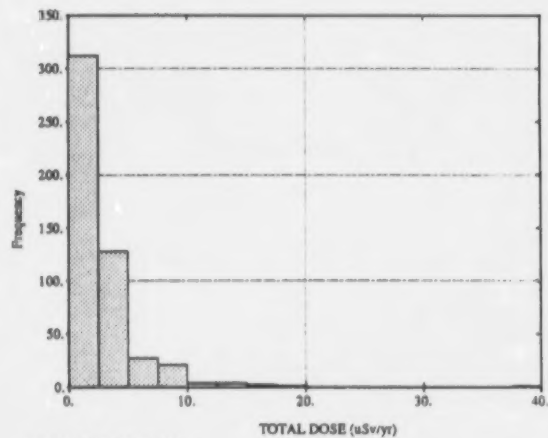
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 2, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.183
STANDARD DEVIATION = 0.195
GEOMETRIC MEAN = 0.128
GEOMETRIC STANDARD DEVIATION = 2.30
MINIMUM = 0.146e-01
MAXIMUM = 2.25

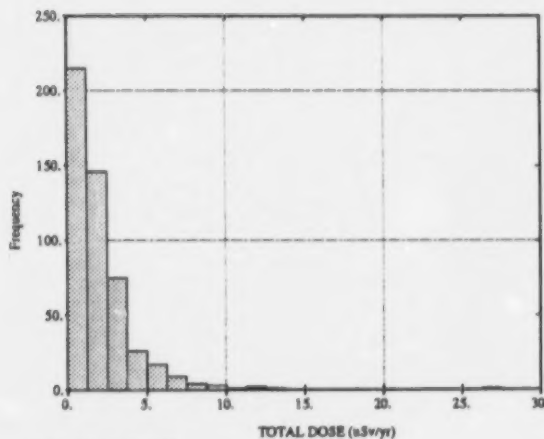
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 2, AT T = 400



SUMMARY STATISTICS:

MEAN = 2.78
STANDARD DEVIATION = 3.03
GEOMETRIC MEAN = 1.94
GEOMETRIC STANDARD DEVIATION = 2.29
MINIMUM = 0.267
MAXIMUM = 38.7

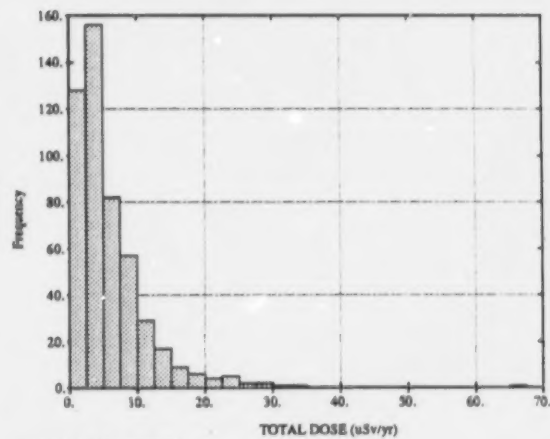
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 2, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.11
STANDARD DEVIATION = 2.16
GEOMETRIC MEAN = 1.51
GEOMETRIC STANDARD DEVIATION = 2.23
MINIMUM = 0.211
MAXIMUM = 26.6

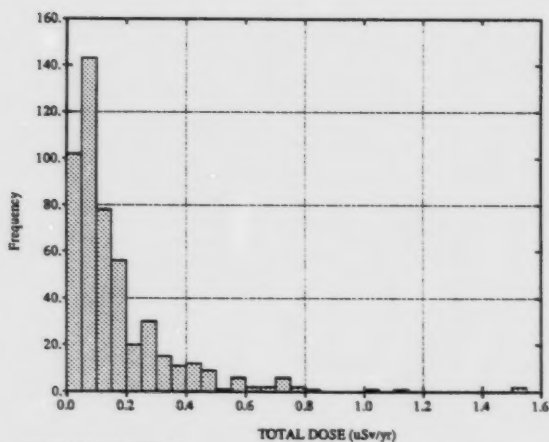
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 2, AT T = 1000



SUMMARY STATISTICS:

MEAN = 6.03
STANDARD DEVIATION = 5.82
GEOMETRIC MEAN = 4.35
GEOMETRIC STANDARD DEVIATION = 2.22
MINIMUM = 0.562
MAXIMUM = 65.6

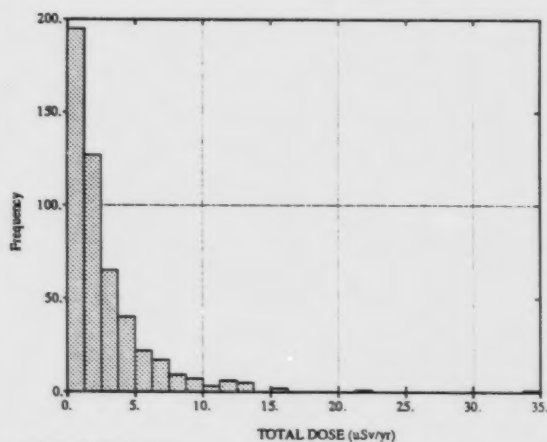
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 2, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.165
STANDARD DEVIATION = 0.182
GEOMETRIC MEAN = 0.109
GEOMETRIC STANDARD DEVIATION = 2.45
MINIMUM = 0.125e-01
MAXIMUM = 1.55

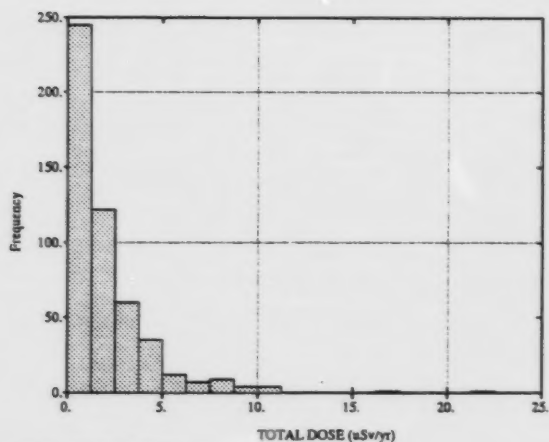
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 2, AT T = 400



SUMMARY STATISTICS:

MEAN = 2.77
STANDARD DEVIATION = 3.16
GEOMETRIC MEAN = 1.81
GEOMETRIC STANDARD DEVIATION = 2.46
MINIMUM = 0.258
MAXIMUM = 34.7

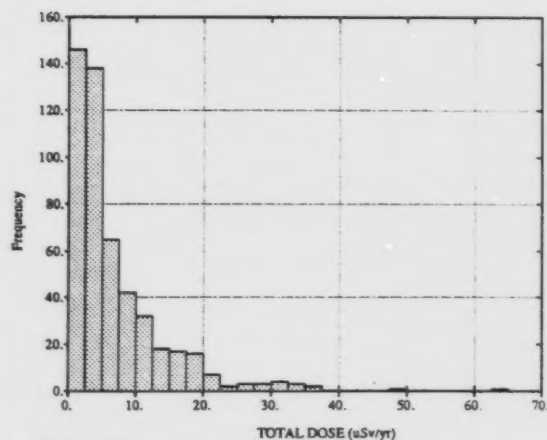
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 2, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.06
STANDARD DEVIATION = 2.25
GEOMETRIC MEAN = 1.37
GEOMETRIC STANDARD DEVIATION = 2.42
MINIMUM = 0.206
MAXIMUM = 22.1

HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 2, AT T = 1000



SUMMARY STATISTICS:

MEAN = 6.91
STANDARD DEVIATION = 7.30
GEOMETRIC MEAN = 4.55
GEOMETRIC STANDARD DEVIATION = 2.47
MINIMUM = 0.707
MAXIMUM = 64.9

FIGURE 5.2.3 : DOSE vs. TIME
FOR SCENARIO 2, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

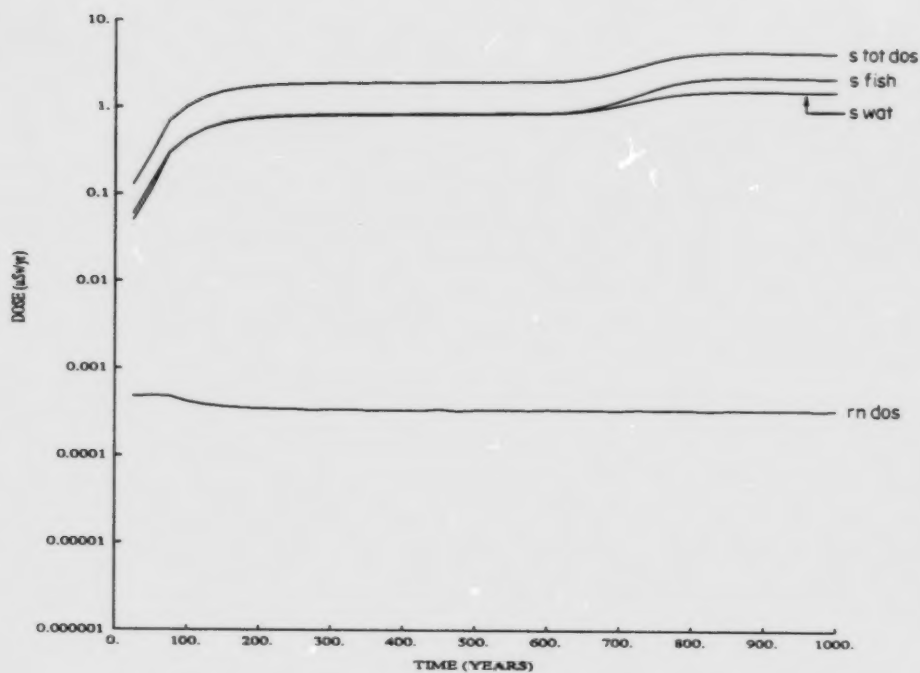


FIGURE 5.2.4 : DOSE vs. TIME
FOR SCENARIO 2, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

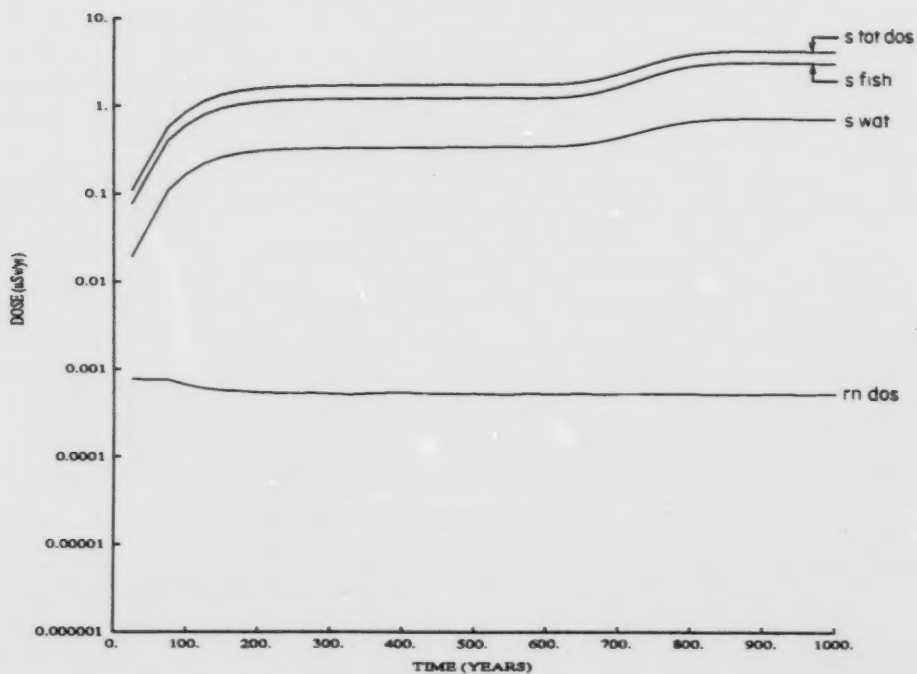


FIGURE 5.2.5 : DOSE vs. TIME
FOR SCENARIO 2, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

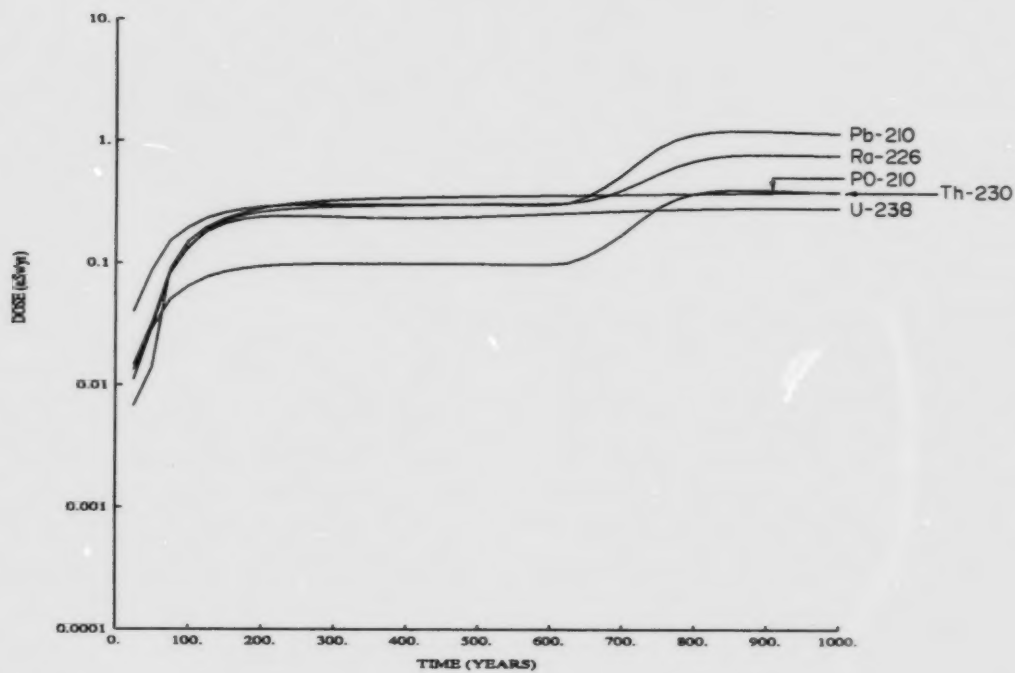


FIGURE 5.2.6 : DOSE vs. TIME
FOR SCENARIO 2, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

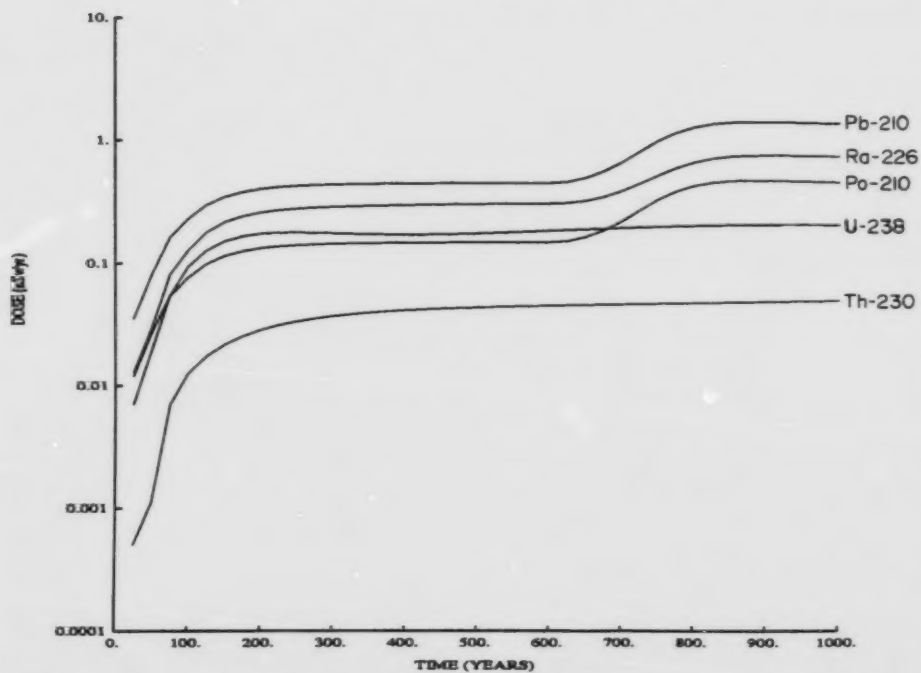


FIGURE 5.3.1a: TOTAL DOSE vs. TIME
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 3,
GEOMETRIC MEAN OF 500 TRIALS

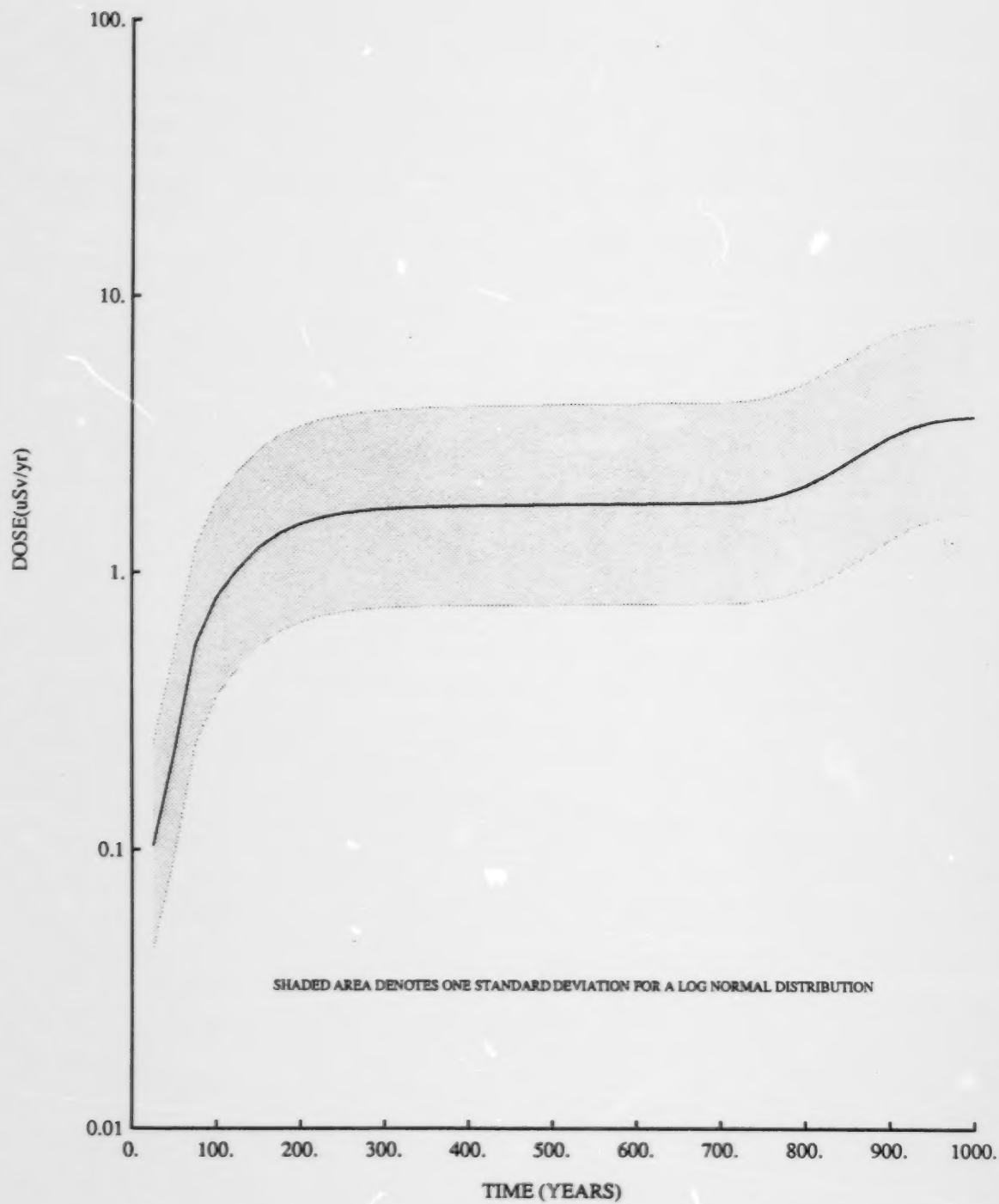
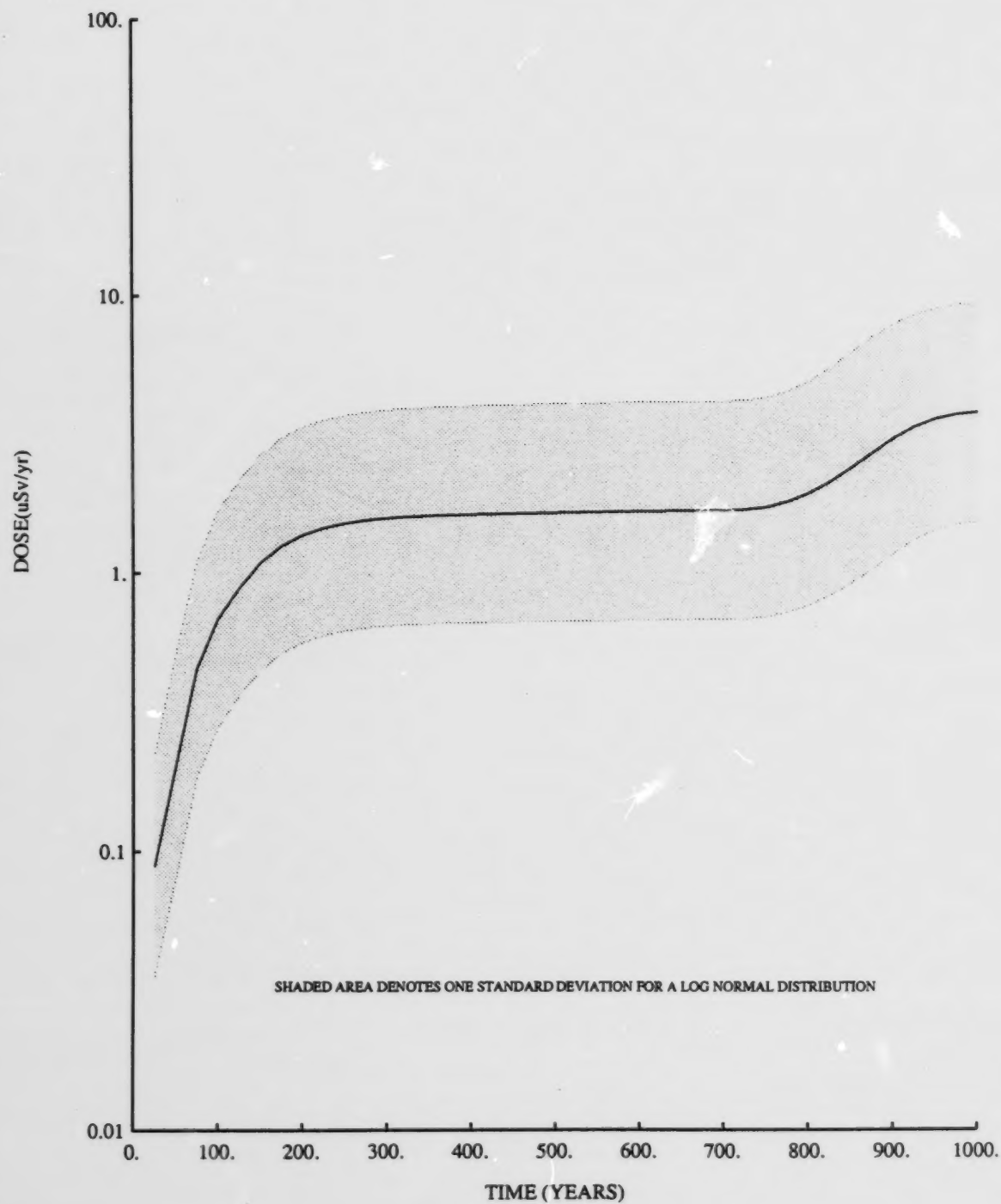
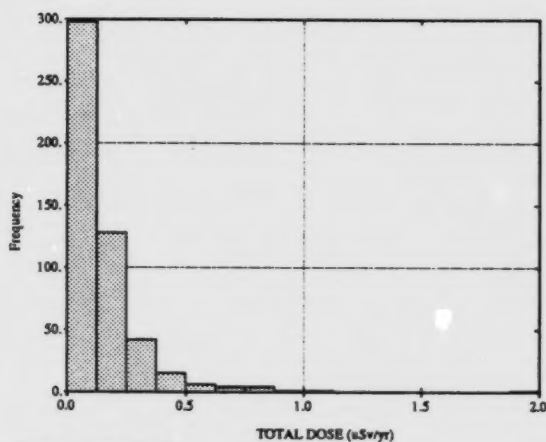


FIGURE 5.3.1b: TOTAL DOSE vs. TIME
AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 3,
GEOMETRIC MEAN OF 500 TRIALS



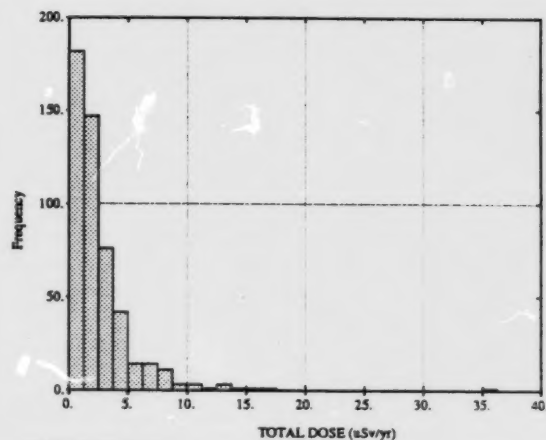
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 3, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.150
STANDARD DEVIATION = 0.164
GEOMETRIC MEAN = 0.104
GEOMETRIC STANDARD DEVIATION = 2.34
MINIMUM = 0.113e-01
MAXIMUM = 1.95

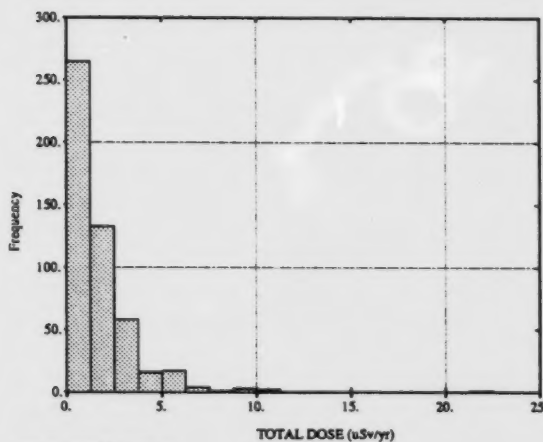
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 3, AT T = 400



SUMMARY STATISTICS:

MEAN = 2.55
STANDARD DEVIATION = 2.79
GEOMETRIC MEAN = 1.77
GEOMETRIC STANDARD DEVIATION = 2.29
MINIMUM = 0.250
MAXIMUM = 35.7

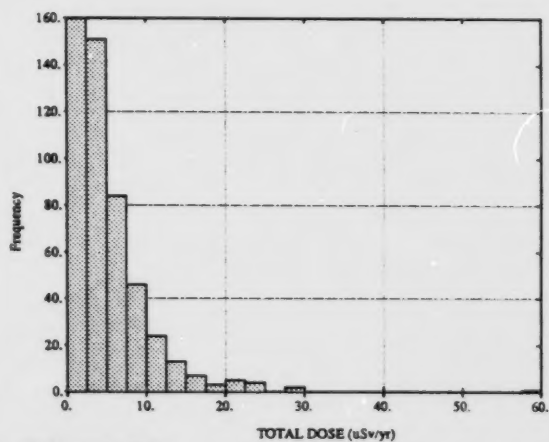
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 3, AT T = 150



SUMMARY STATISTICS:

MEAN = 1.75
STANDARD DEVIATION = 1.84
GEOMETRIC MEAN = 1.24
GEOMETRIC STANDARD DEVIATION = 2.27
MINIMUM = 0.161
MAXIMUM = 22.5

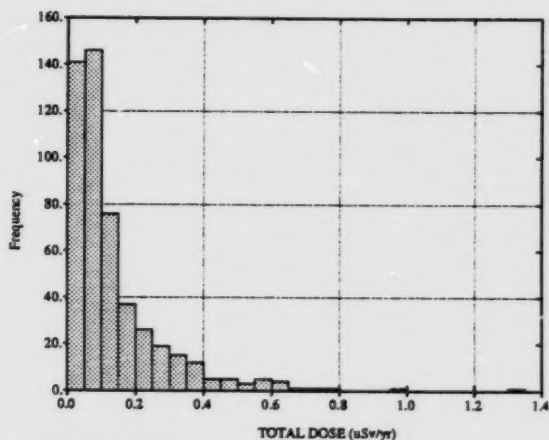
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 3, AT T = 1000



SUMMARY STATISTICS:

MEAN = 5.26
STANDARD DEVIATION = 5.16
GEOMETRIC MEAN = 3.78
GEOMETRIC STANDARD DEVIATION = 2.13
MINIMUM = 0.476
MAXIMUM = 59.5

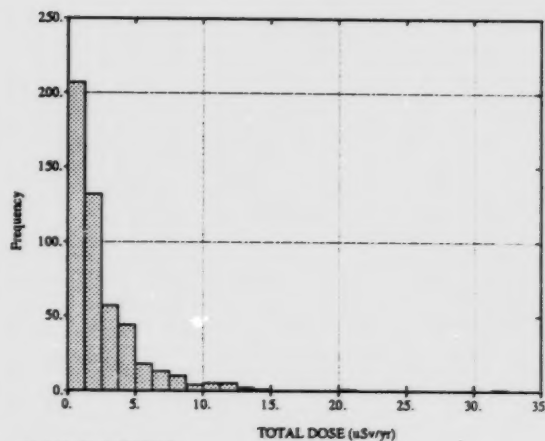
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 3, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.137
STANDARD DEVIATION = 0.155
GEOMETRIC MEAN = $0.885e-01$
GEOMETRIC STANDARD DEVIATION = 2.50
MINIMUM = $0.946e-02$
MAXIMUM = 1.35

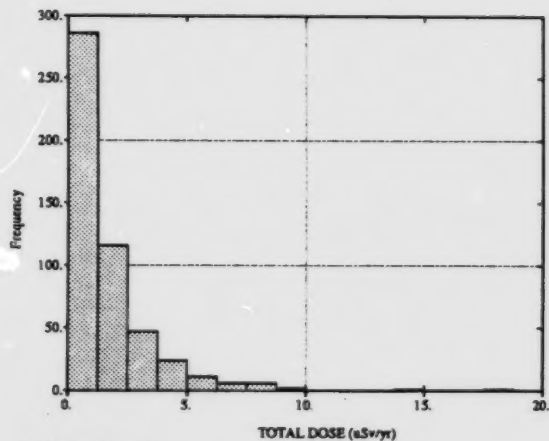
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 3, AT T = 400



SUMMARY STATISTICS:

MEAN = 2.53
STANDARD DEVIATION = 2.88
GEOMETRIC MEAN = 1.65
GEOMETRIC STANDARD DEVIATION = 2.46
MINIMUM = 0.233
MAXIMUM = 31.8

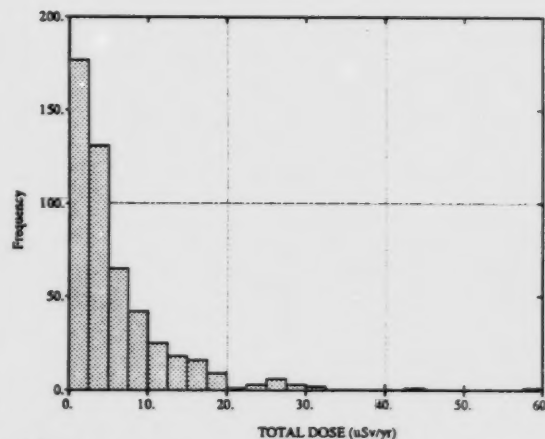
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 3, AT T = 150



SUMMARY STATISTICS:

MEAN = 1.66
STANDARD DEVIATION = 1.84
GEOMETRIC MEAN = 1.09
GEOMETRIC STANDARD DEVIATION = 2.43
MINIMUM = 0.154
MAXIMUM = 18.2

HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 3, AT T = 1000



SUMMARY STATISTICS:

MEAN = 5.96
STANDARD DEVIATION = 6.34
GEOMETRIC MEAN = 3.92
GEOMETRIC STANDARD DEVIATION = 2.48
MINIMUM = 0.621
MAXIMUM = 58.6

FIGURE 5.3.3 : DOSE vs. TIME
FOR SCENARIO 3, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR



FIGURE 5.3.4 : DOSE vs. TIME
FOR SCENARIO 3, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

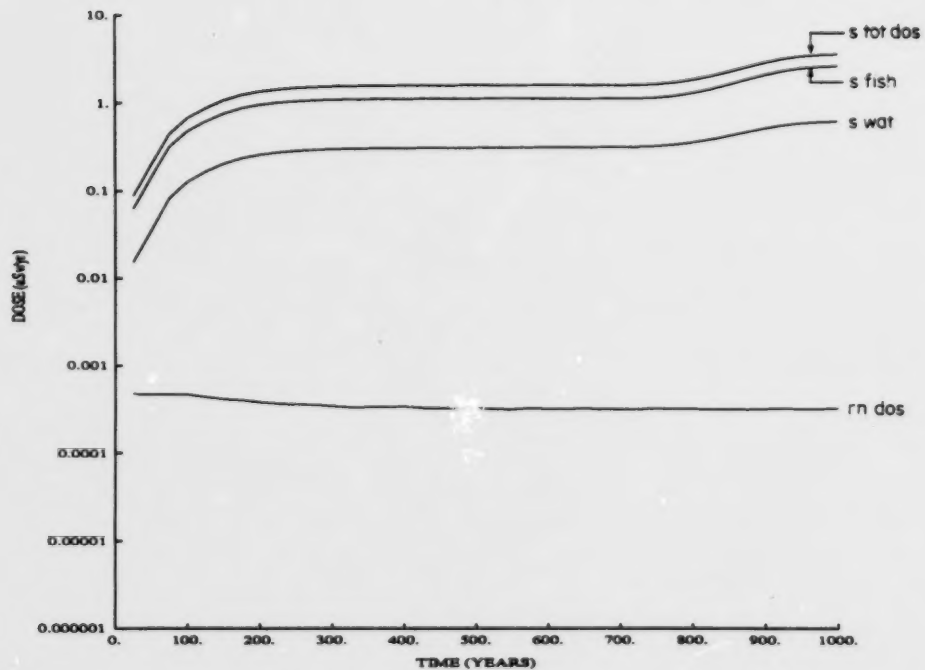


FIGURE 5.3.5 : DOSE vs. TIME
FOR SCENARIO 3, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

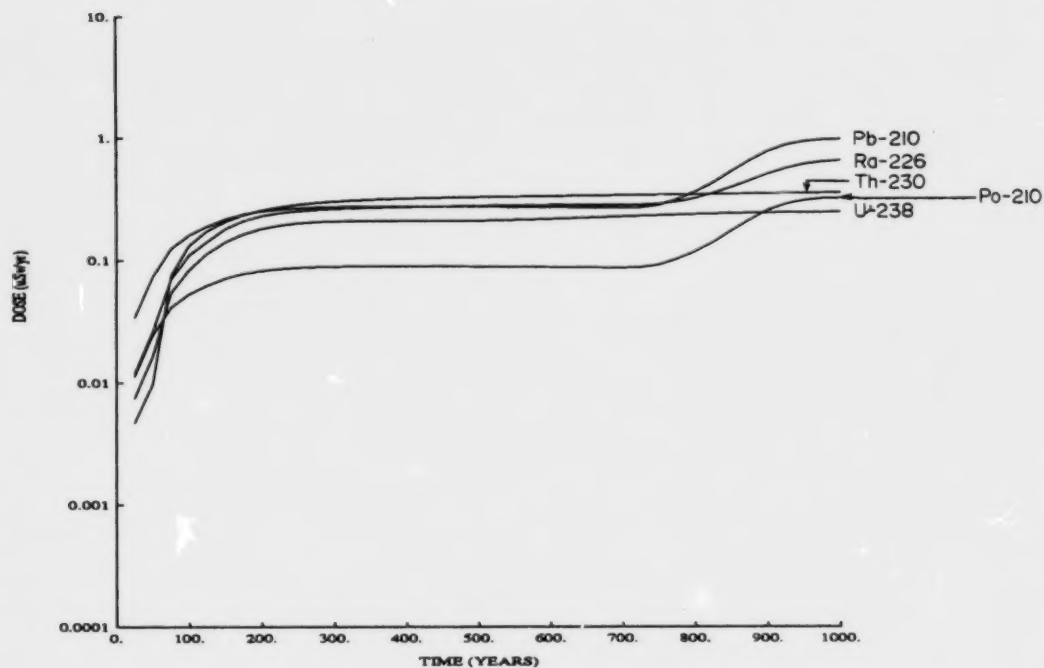


FIGURE 5.3.6 : DOSE vs. TIME
FOR SCENARIO 3, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

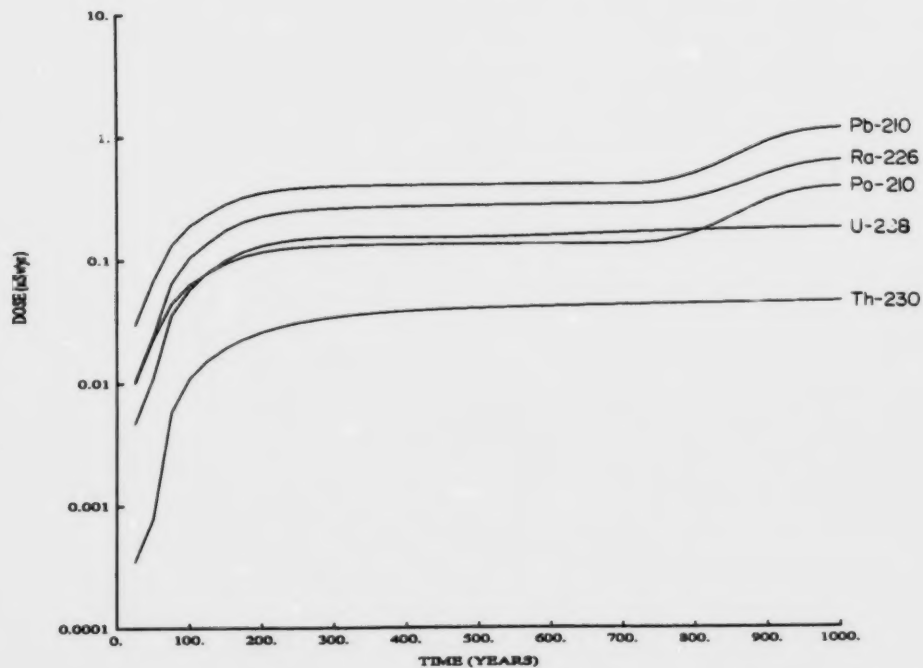


FIGURE 5.4.1a: TOTAL DOSE vs. TIME
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 4,
GEOMETRIC MEAN OF 500 TRIALS

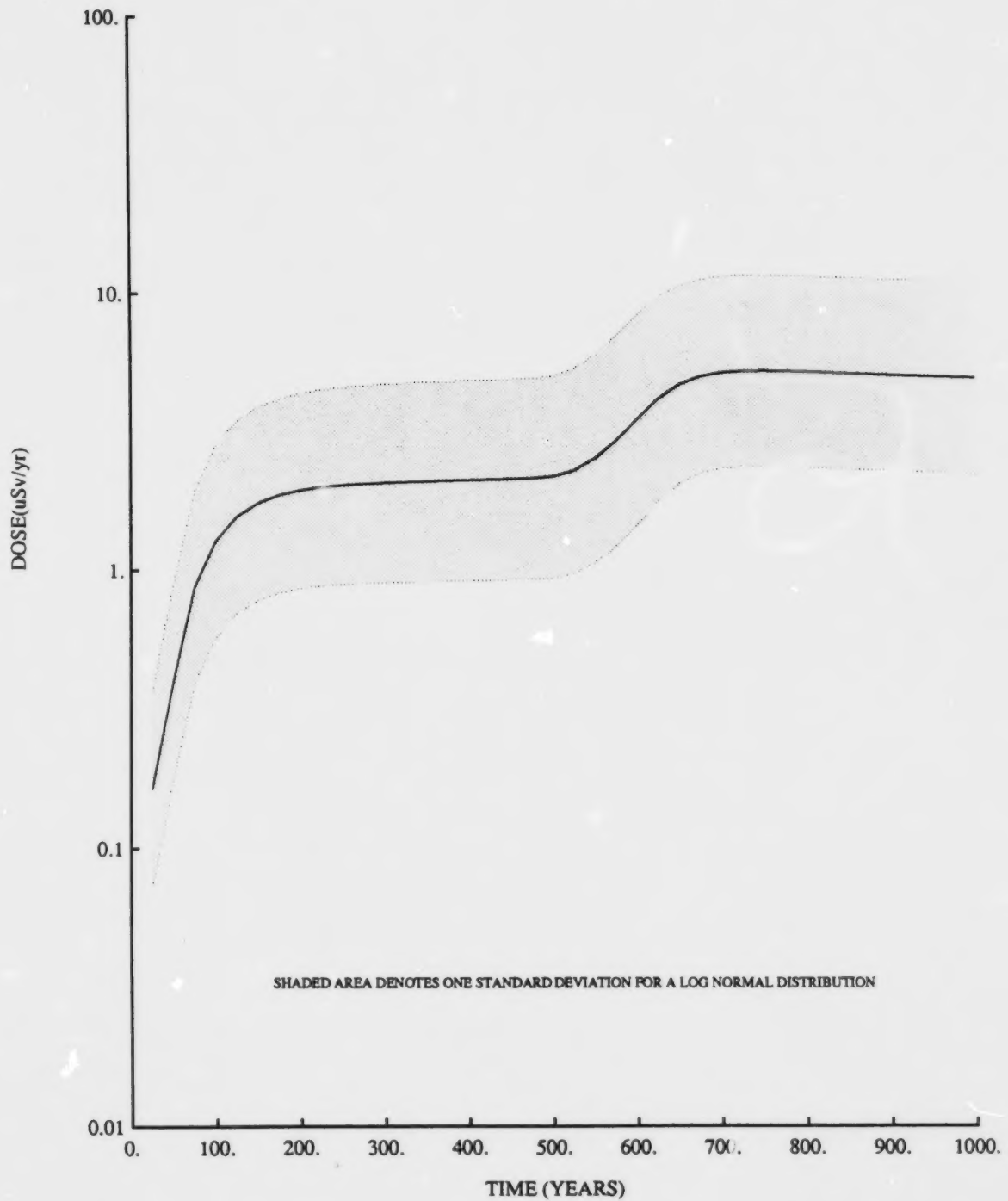
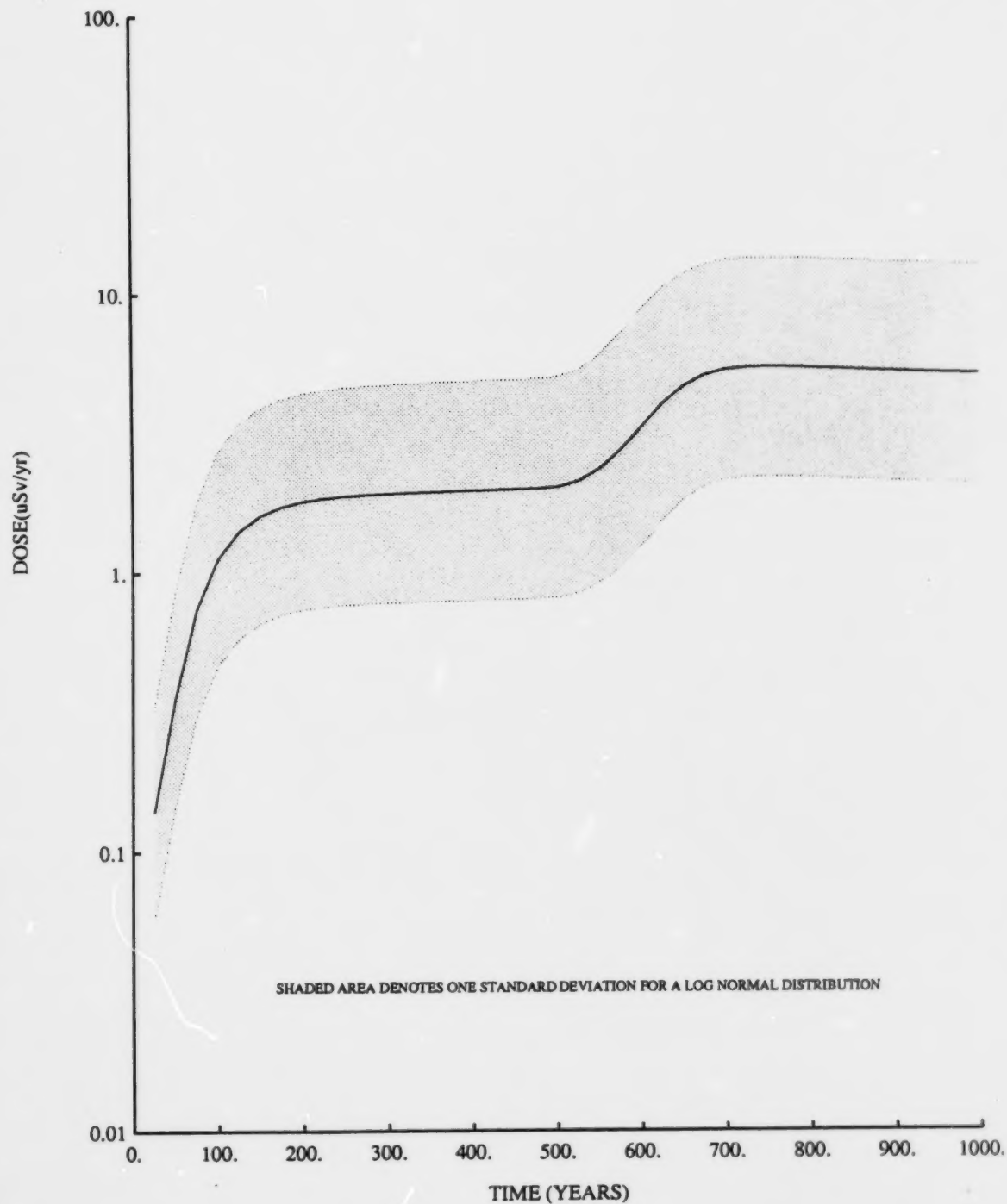
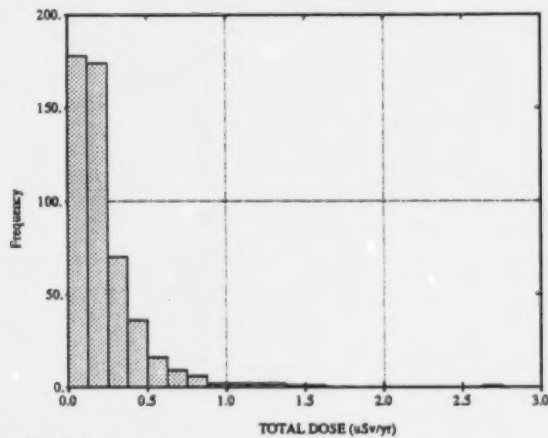


FIGURE 5.4.1b: TOTAL DOSE vs. TIME
AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 4,
GEOMETRIC MEAN OF 500 TRIALS



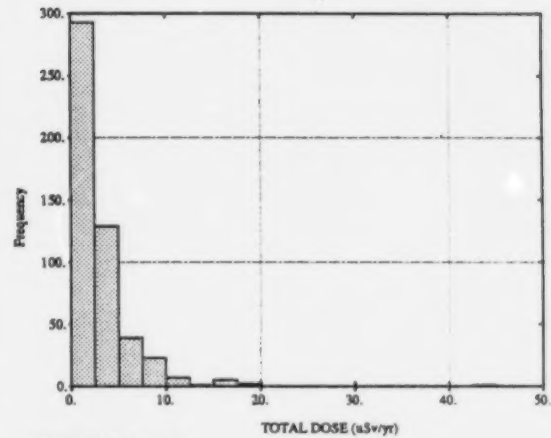
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 4, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.232
STANDARD DEVIATION = 0.240
GEOMETRIC MEAN = 0.165
GEOMETRIC STANDARD DEVIATION = 1.26
MINIMUM = 0.195e-01
MAXIMUM = 2.67

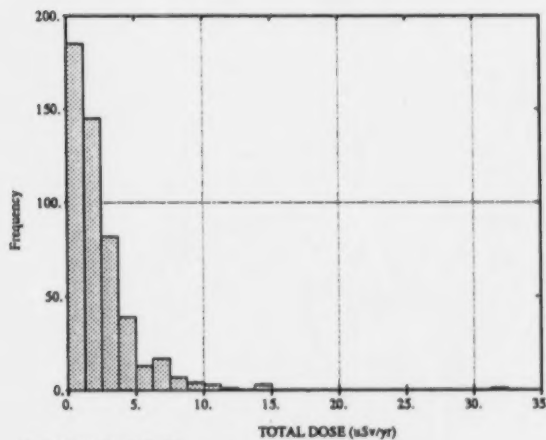
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 4, AT T = 400



SUMMARY STATISTICS:

MEAN = 3.05
STANDARD DEVIATION = 3.34
GEOMETRIC MEAN = 2.12
GEOMETRIC STANDARD DEVIATION = 1.30
MINIMUM = 0.280
MAXIMUM = 42.7

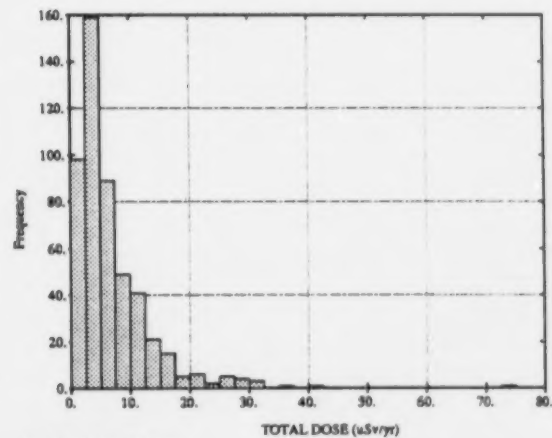
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 4, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.44
STANDARD DEVIATION = 2.51
GEOMETRIC MEAN = 1.75
GEOMETRIC STANDARD DEVIATION = 2.23
MINIMUM = 0.248
MAXIMUM = 31.4

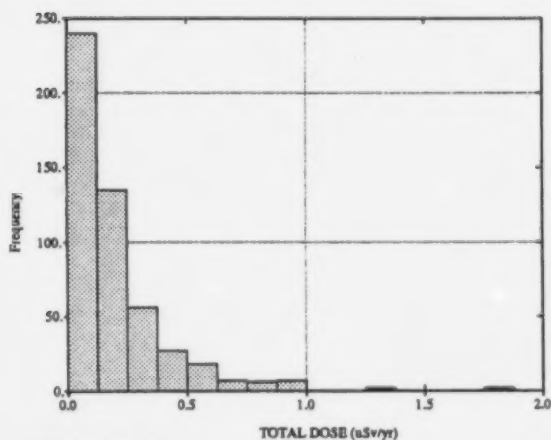
HISTOGRAM OF TOTAL DOSE
AT HIDDEN BAY RECEPTOR
FOR SCENARIO 4, AT T = 1000



SUMMARY STATISTICS:

MEAN = 6.95
STANDARD DEVIATION = 6.71
GEOMETRIC MEAN = 5.00
GEOMETRIC STANDARD DEVIATION = 2.23
MINIMUM = 0.643
MAXIMUM = 74.1

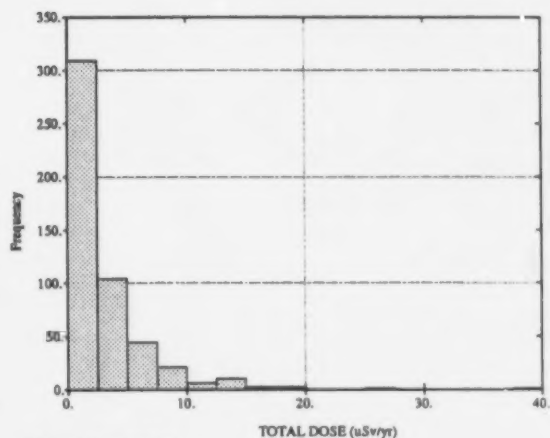
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 4, AT T = 25



SUMMARY STATISTICS:

MEAN = 0.207
STANDARD DEVIATION = 0.222
GEOMETRIC MEAN = 0.139
GEOMETRIC STANDARD DEVIATION = 2.40
MINIMUM = 0.174e-01
MAXIMUM = 1.83

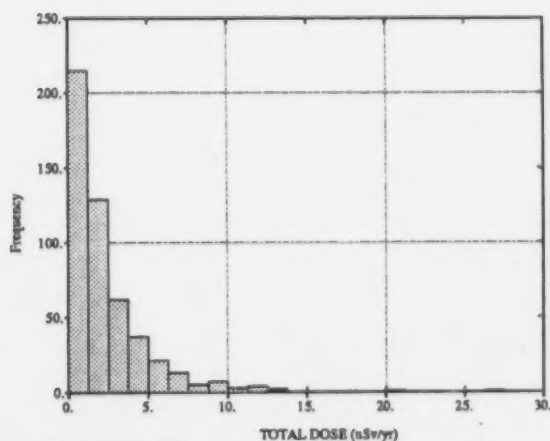
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 4, AT T = 400



SUMMARY STATISTICS:

MEAN = 3.06
STANDARD DEVIATION = 3.52
GEOMETRIC MEAN = 1.99
GEOMETRIC STANDARD DEVIATION = 2.47
MINIMUM = 0.288
MAXIMUM = 38.6

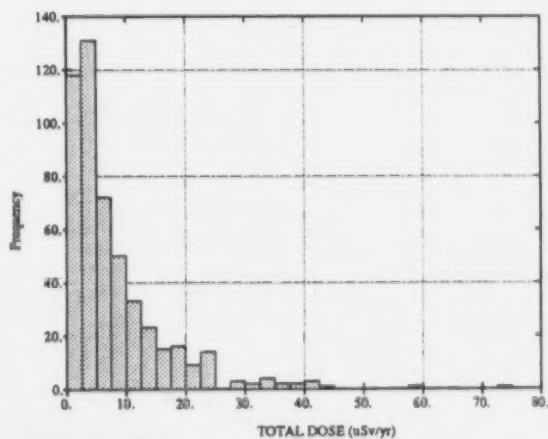
HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 4, AT T = 150



SUMMARY STATISTICS:

MEAN = 2.43
STANDARD DEVIATION = 2.67
GEOMETRIC MEAN = 1.61
GEOMETRIC STANDARD DEVIATION = 2.43
MINIMUM = 0.332
MAXIMUM = 26.7

HISTOGRAM OF TOTAL DOSE
AT WOLLASTON POST RECEPTOR
FOR SCENARIO 4, AT T = 1000



SUMMARY STATISTICS:

MEAN = 8.04
STANDARD DEVIATION = 8.53
GEOMETRIC MEAN = 5.28
GEOMETRIC STANDARD DEVIATION = 2.48
MINIMUM = 0.800
MAXIMUM = 73.5

FIGURE 5.4.3 : DOSE vs. TIME
FOR SCENARIO 4, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

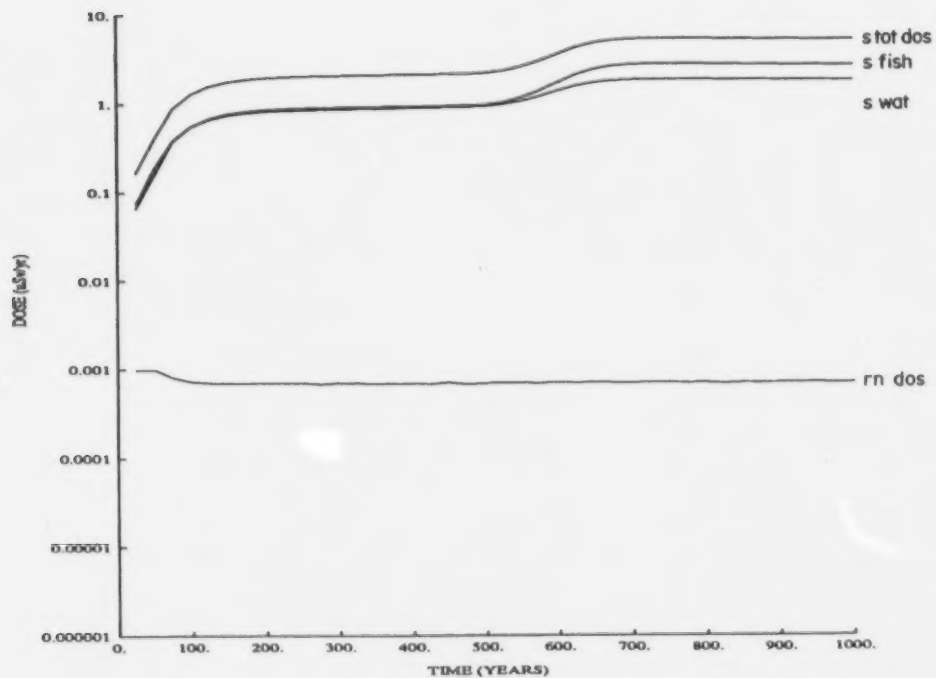


FIGURE 5.4.4 : DOSE vs. TIME
FOR SCENARIO 4, BY PATHWAY
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR

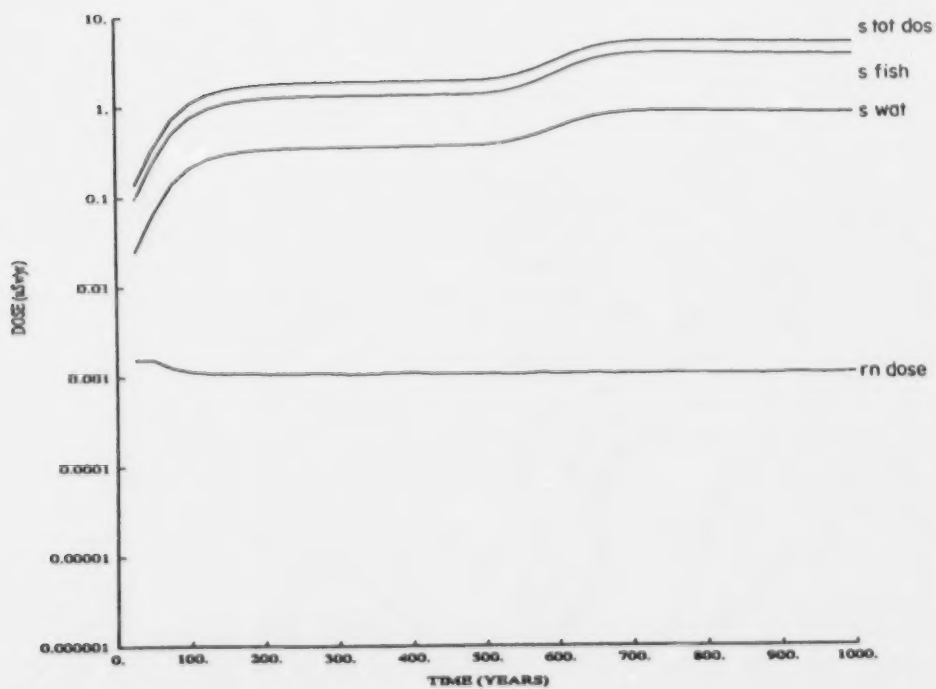


FIGURE 5.4.5 : DOSE vs. TIME
FOR SCENARIO 4, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT HIDDEN BAY RECEPTOR

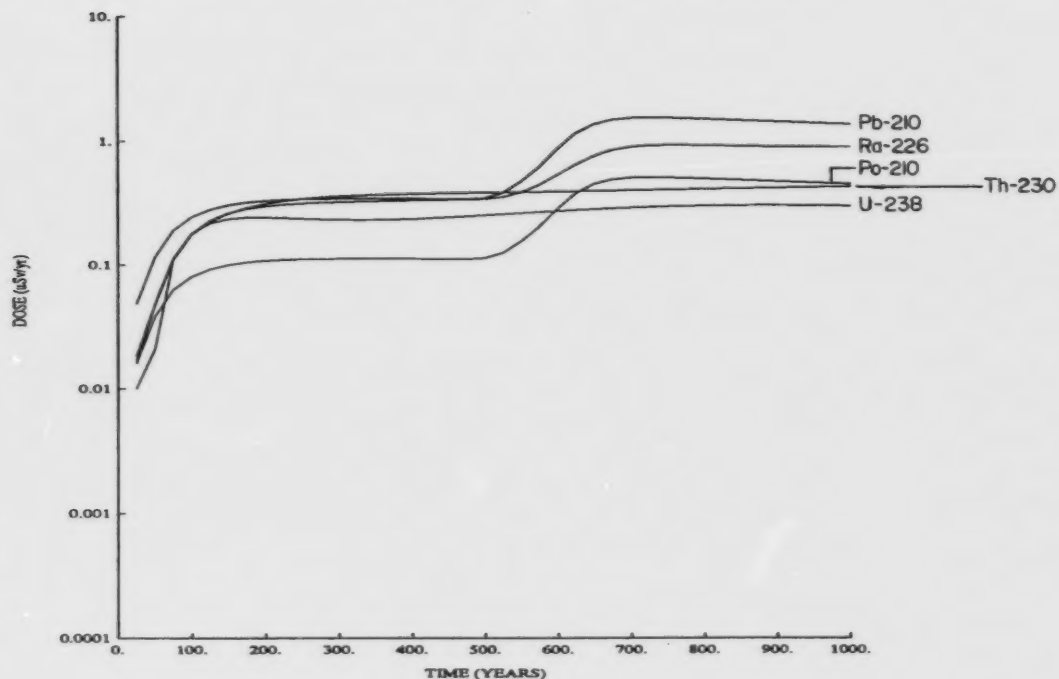
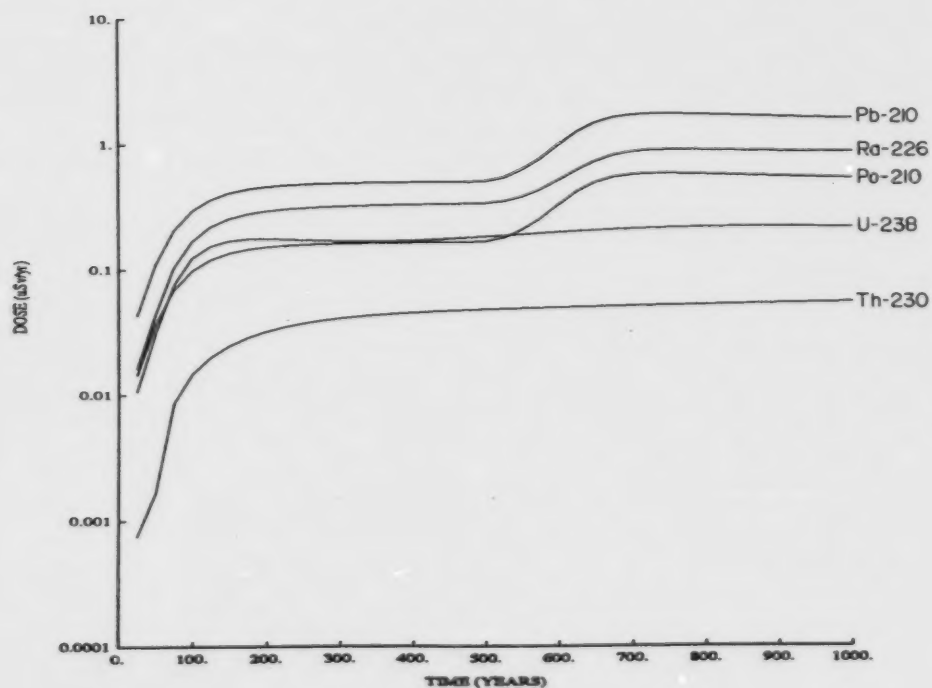


FIGURE 5.4.6 : DOSE vs. TIME
FOR SCENARIO 4, BY RADIONUCLIDE
GEOMETRIC MEAN OF 500 TRIALS
AT WOLLASTON POST RECEPTOR



(compare Figures 5.1.3, 5.2.3, 5.3.3 and 5.4.3 for the Hidden Bay receptor for the different management scenarios; compare Figures 5.1.4, 5.2.4, 5.3.4 and 5.4.4 for the Wollaston Lake receptor for the different management scenarios). The aquatic dose does not vary substantially for the different management scenarios, because the management scenarios mainly affect the amount of rainfall which infiltrates the surface of the tailings - this comprises only a small component of the tailings water budget. The main flux of water through the tailings is caused by groundwater flow from the north ridge. Covering of the tailings results in substantial reductions in doses through atmospheric pathways, but these doses are relatively insignificant in comparison with the aquatic pathways.

Of the total dose, the fish contribution is larger than the drinking water contribution. The difference between drinking water and fish consumption dose rate is smaller for Hidden Bay (Figure 5.1.3) than for Wollaston Lake (Figure 5.1.4) because the Hidden Bay receptor consumes fish caught in both Hidden Bay and Wollaston Lake, while Wollaston Lake receptors consume fish only from Wollaston Lake. The Hidden Bay dose rate from drinking water is somewhat larger than the corresponding dose rate for Wollaston Lake because the radionuclide activity in Hidden Bay is marginally higher than that in Wollaston Lake (compare Figure 5.5a to 5.5b). The drinking water supply originates from a completely mixed bay and lake, respectively for the Hidden Bay and Wollaston Lake potential receptors. But, the dose rate due to fish consumption is slightly higher for the Wollaston Lake potential receptor than the dose rate for Hidden Bay. This occurs despite the radionuclide activity in Hidden Bay fish being larger than in Wollaston Lake fish because of the food habits of the populations at the two receptor locations. The Hidden Bay receptor is assumed to consume about 30% of his fish from Hidden Bay and 70% from Wollaston Lake, and has an occupancy factor of about 40%. The Wollaston Lake receptor consumes all his fish from Wollaston Lake, and has an occupancy factor of nearly 100%. The occupancy factor has a stronger effect upon the dose rate calculation than the smaller amount of fish consumed by the receptor located at the Hidden Bay.

The dose rate, S_{air} , is the total dose rate from all atmospheric sources of both a direct and indirect origin (radon, dust inhalation, vegetable and berry consumption, and groundshine). The radionuclide impact upon vegetables/berries is derived strictly from dust-fall and root uptake from soil contaminated by dust-fall because it is assumed that vegetables are not irrigated. The calculations indicate that radon inhalation is the

largest contribution to dose from all atmospheric pathways. Groundshine is the next most important contributor to dose for Hidden Bay, although groundshine approaches the dose attributable to other pathways at 1,000 years due to ground level buildup. Vegetable intake is the next most important pathway for the Wollaston Lake receptor during the first two centuries. The Hidden Bay dose due to vegetable/berry consumption is lower than for the Wollaston Lake receptor because there are no vegetables grown at the Hidden Bay receptor location, and only a small quantity of berries consumed. The geometric mean dose rate due to vegetable/berry consumption is larger than the mean dust inhalation dose rate for the initial simulation period for the Hidden Bay receptor, but lower for the latter part of the simulation period; however, the confidence interval, based on one standard deviation, for these two exposure routes overlap.

The dose rate from each of the atmospheric pathways is somewhat larger for the Wollaston Lake receptor than for the Hidden Bay receptor. This results from the greater wind frequency in the direction of Wollaston Lake, which dominates over the proximity factor - Hidden Bay being much closer than Wollaston Lake to the tailings (see Section E3 in Appendix E).

Of the four radionuclides modelled, lead-210 makes a slightly larger contribution than Ra-226 for the Wollaston Lake receptor (Figure 5.1.6) and for much of the period for the Hidden Bay receptor. The Pb-210 dose rate follows that of Ra-226 because their lake concentrations are nearly the same (see Figure 5.5) (due to Pb-210 ingrowth from Ra-226). The dose rate is slightly larger due to the relative differences in bioconcentration and dose conversion factors. Th-230 makes a significant contribution to dose during the first several hundred years at the Hidden Bay receptor. Afterwards, the Th-230 dose rate is lower than that of Ra-226 and Pb-210. The dose rate from total uranium (uranium-238 plus uranium-234) and Po-210 are generally lower than those of Pb-210. The dose rate from Po-210 is lower than that from Pb-210, despite their specific activities being quite close in the lake water. This results because of differences in bioconcentration and dose conversion factors. The trend of radionuclide concentration in the lake is discussed in Section 5.2.

For the management scenarios modelled, the major differences relate to the effect that the cover has upon atmospheric transport of radionuclides. Radon exhalation is the largest airborne dose to either the Hidden Bay or to the Wollaston Lake receptor (see

respectively Figures 5.1.3, 5.2.3, 5.3.3, 5.4.3 and 5.1.4, 5.2.4, 5.3.4, 5.4.4). The installation of a till cover reduces the radon dose in comparison to the base case. The clay cover reduces the radon dose even further. The installation of the waste rock cover is calculated to have a marginal effect upon the dose rate arising from radon inhalation compared to the base case. The waste rock cover reduces the radon flux by providing some hold-up time for radon decay within the cover, but at the same time contributes a small amount to the flux due to radon emanation from residual uranium minerals containing Ra-226 in the waste rock.

For the management scenarios, the dose rate derived from each radionuclide (see Figures 5.1.5, 5.2.5, 5.3.5, 5.4.5 for the Hidden Bay receptor; see Figures 5.1.6, 5.2.6, 5.3.6, 5.4.6 for Wollaston Lake receptor) does not show a substantive change between scenarios. This occurs because the dose rate from each radionuclide is dominated by aquatic pathways, a route which is relatively insensitive to the management scenarios. The timing of the projected increase in dose rate arising from the base case (ca 500-600 year) is calculated to change somewhat in the different management scenarios (ca 600 to 800 year for Scenario 2, ca 800 to 1,000 year for Scenario 3).

Histograms of dose over time are also given in Figures 5.1, 5.2, 5.3 and 5.4. Histograms are given for 25, 150, 400 and 1,000 years. They are essentially the same for all scenarios. The histograms are typical of calculations which approach a log-normal distribution - most of the calculated values are clustered at the lower end of concentration values with a few values which are substantially higher.

5.2 Comparison of Model Calculations for Dose Rate to that from Other Environments

Maximum predicted total incremental doses of 10 uSv/yr (geometric mean plus one standard deviation - Figure 5.1.1a) are relatively low. In comparison, the estimated annual effective dose equivalent from natural sources of U-238 decay chain radionuclides is 1,044 uSv/yr in areas of normal background concentrations (UNSCEAR, 1982), which is about 100-fold greater than the predicted maximum dose equivalent due to exposure to the Rabbit Lake tailings. A dose of 10 uSv/yr is essentially imperceptible within the range of background variation, and is only 20% of the AECB proposed de minimis dose of 50 uSv/yr. Thus, based on this analysis, maximum doses predicted at the two receptors

located near the Rabbit Lake tailings remain negligible over the 1,000 year time frame of this model.

5.3 Calculated Activity of Radionuclides in the Lakes

The time trend of dose rate calculated over time is determined by the time trend of radionuclide activity in Hidden Bay and Wollaston Lake because aquatic pathways make a much larger contribution to dose than do atmospheric pathways.

Concentrations of the radionuclides in the three lakes are given in Figures E.2.11 (Parks Lake), 5.5a (Hidden Bay) and 5.5b (Wollaston Lake). The profiles for Parks Lake and Hidden Bay show essentially the same time trend for most radionuclides, but have different concentrations. The time trend predicted for each lake follows the time trend of the groundwater model. The different concentrations are caused mainly by the differences in hydrology - Parks Lake has a much smaller degree of dilution than does Hidden Bay. In addition, Hidden Bay is affected by exchange flow with Wollaston Lake. The values are reasonable in that they are within an order of magnitude of values for a conservative substance - sediment exchange removes the rest to the sediments. The predicted values cannot be compared to observed values because of the substantial input from other background sources to Wollaston Lake.

The calculated activity of radionuclides in Hidden Bay is of the same order of magnitude as that of Wollaston Lake, except for Th-230 which is an order of magnitude larger in Hidden Bay. The closeness of values reflects the effects of exchange flow between the lake and bay. The calculated activity of Pb-210 and Po-210 is reasonably close in Hidden Bay, but the values have larger differences in Wollaston Lake. These differences for Po-210 and Th-230 result from sediment-water interactions.

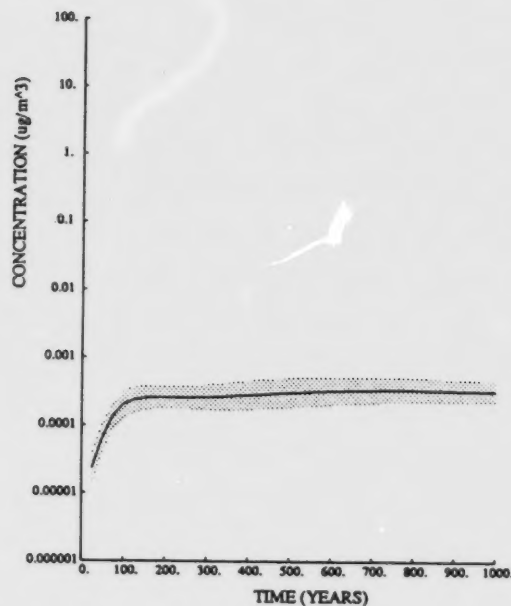
These calculations agree with monitoring data which suggest that there is no detectable differences in uranium concentrations and radium-226 activity between the bay and the lake. Th-230 values are not well known due to detection limit values.

The time trend of radionuclide activity and absolute magnitude is driven by trend of radionuclide release from the tailings through the seven groundwater pathways. The initial plateau in dose, between 0 to 300 years, is caused by a constant flushing rate of

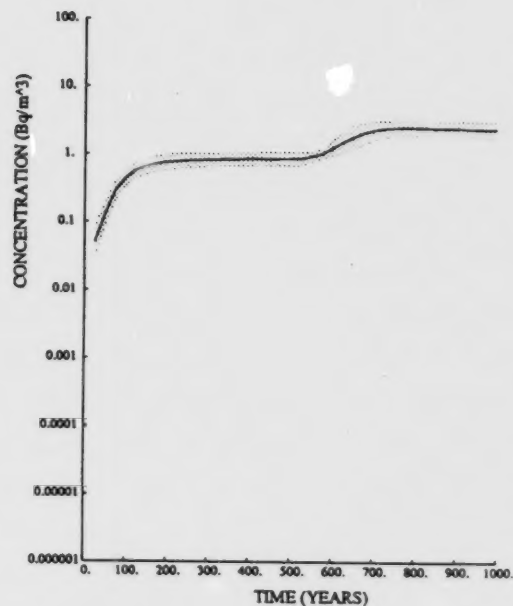
FIGURE 5.5a

CONCENTRATION vs. TIME
IN HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

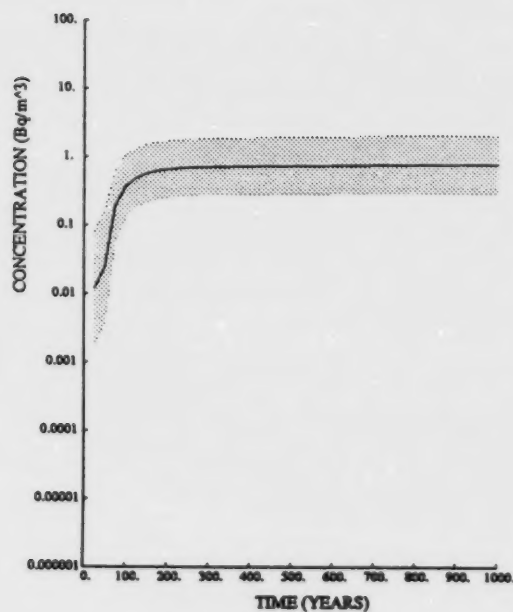
FOR U-238



FOR Ra-226



FOR Th-230



FOR Pb-210

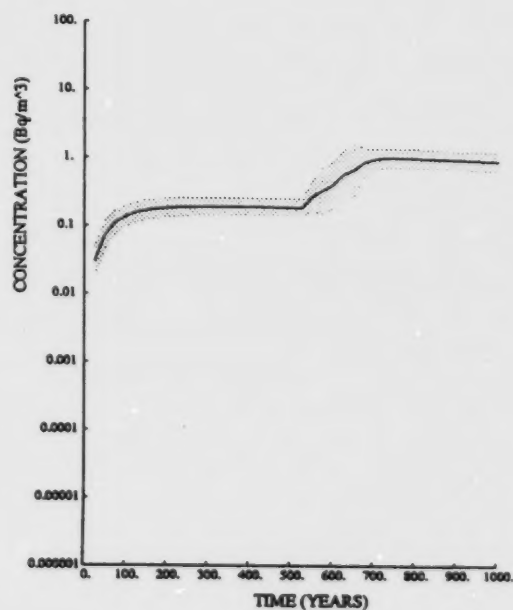
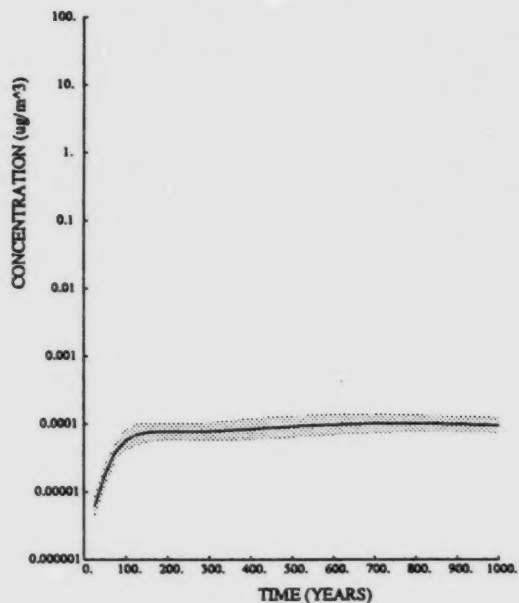


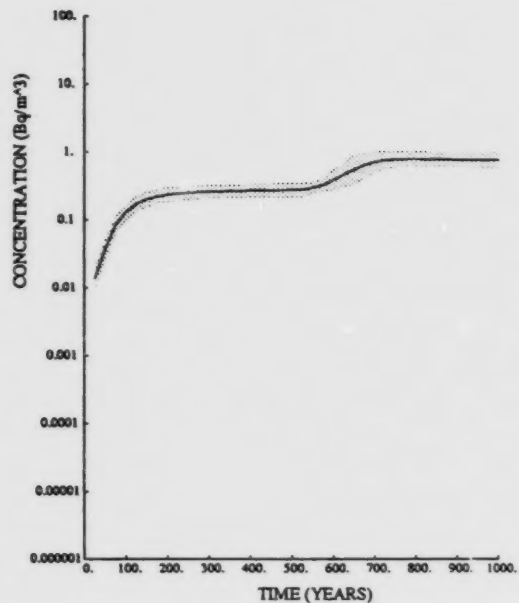
FIGURE 5.5b

CONCENTRATION vs. TIME
IN WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

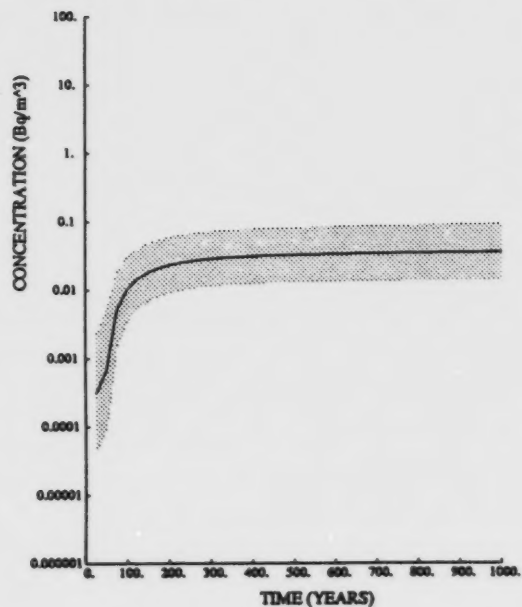
FOR U-238



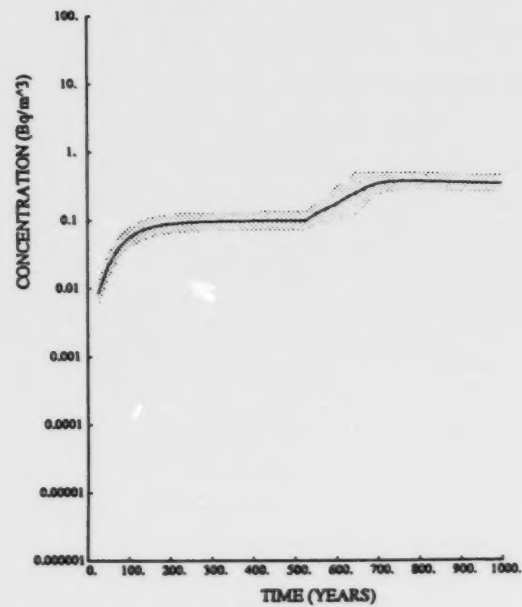
FOR Ra-226



FOR Th-230



FOR Pb-210



radionuclides (mainly radium-226 and lead-210). At approximately 400 years, all the gypsum, anglesite and barite, contained in the two surficial tailings boxes near the south dam, wash out. Porewater from these boxes flow to a lower box, and directly to groundwater. This results in a large residual Ra-226 concentration in the porewater and on adsorption sites being flushed out of the tailings and groundwater pathways for the remainder of the simulation period. These higher concentrations cause higher lake concentrations and a higher dose rate.

This one large jump would be reduced to a series of smaller jumps if the tailings boxes were divided up into a group of smaller boxes. This would not, however, change the overall magnitude of dose rate near the end of the simulation period. The addition of a few more boxes in future work would be worthwhile, but its priority needs further consideration.

5.4 Sensitivity Analysis

Parameters which are of particular concern to this investigation were selected for investigation by sensitivity analysis. Parameters selected are those for which there is considerable uncertainty in the measure of central tendency of their frequency distribution. The two parameters evaluated here are the depth of the unsaturated zone in the tailings and the sorption coefficient for various radionuclides in the tailings.

The depth of the unsaturated zone in the tailings was estimated using finite element modelling of the tailings and local groundwater system. This modelling shows inconsistencies in the permeability and water budget database. It suggested that the groundwater table could be as deep as 20 m. Accordingly, a sensitivity analysis was made assuming that the unsaturated zone was approximately 20 m in depth. For modelling purposes, box 3 (slimes) and box 7 (coarse) were also made to be unsaturated, in addition to Boxes 1, 2 and 6 for the base case.

The resultant calculations (not shown) indicate that the dose rate is relatively insensitive to the depth of the unsaturated zone, and that it is essentially the same as the results given in Figure 5.1.

For a second sensitivity test, the tailings sorption coefficients for radionuclides were changed from a mode of 100 for the triangular distribution to a mode of 1. These new values were the calibration used in the Demonstration of UTAP for Northern Saskatchewan (BEAK, 1986). Its calibration is appropriate because it was assumed that coprecipitation dominated radium-226 and Pb-210 chemistry in the source term.

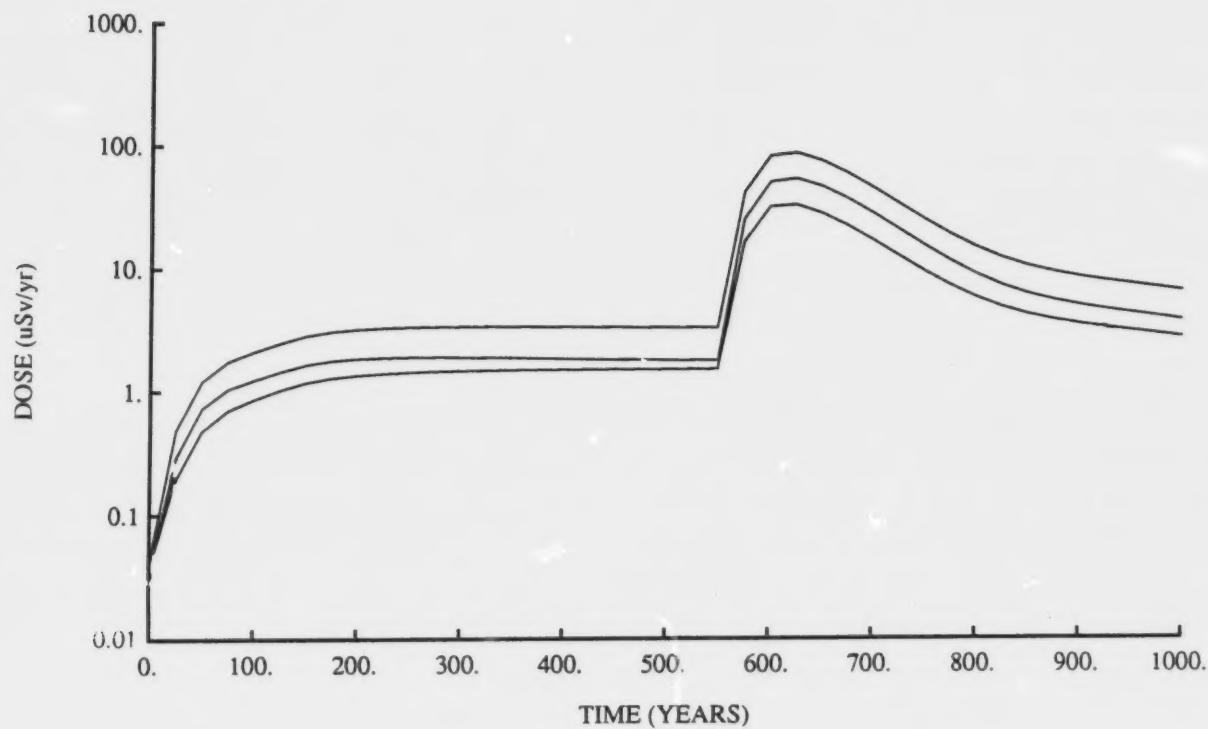
The dose rate for this assumption (K_D (distribution or sorption coefficient) = 1 for mode of distribution) is given in Figure 5.6. It shows a similar dose rate to the base case for the first 500 years, and then an order of magnitude increase in dose rate at approximately 600 years. This increase is of concern for two reasons: it occurs in the middle of the calculation period, rather than immediately after decommissioning, and potentially could constitute a surprise for regulatory authorities. Secondly, its frequency distribution is substantially above the 1 to 10 $\mu\text{Sv}/\text{year}$ range calculated for the most probable cases, although the geometric mean dose rate remains below the proposed AECS de minimis level.

The peak occurs because radium-226 from tailings boxes 6 and 7 washes out completely at 600 years. This results from the secondary precipitates, which control Ra-226, gypsum, anglesite and barite completely dissolving at this time. Flow pathways from boxes 6 and 7 connect directly to the external environment, as well as to lower boxes. Accordingly, when Ra-226 in the tailings is completely released from these boxes, it washes out to Hidden Bay through the south dam. A portion of the Ra-226 which washes out is retained in the dam due to adsorption reactions.

In this project, the calibration from BEAK (1986) was altered due to the uncertainty associated with sorption reactions in the tailings and in the groundwater (tailings dam) pathways. With a K_D of 1.0 in the tailings, one assumes that all radium is tied up only by coprecipitation reactions included in the model and that relatively little is adsorbed by other mechanisms such as ion exchange or coprecipitation reactions with other minerals (e.g., goethite and aluminum hydroxide). When all coprecipitate controlling phases are washed out, there is essentially no mechanism for sorbing Ra-226. This is unlikely. Ion exchange and other reversible sorption processes are expected to sorb some Ra-226 onto the solid phase.

FIGURE 5.6

DOSE vs. TIME
FOR SCENARIO 1, BY PATHWAY
GEOMETRIC MEAN
FOR HIDDEN BAY RECEPTOR



It was also decided that the adsorption coefficient in the tailings themselves and in the till at the toe of the dam would change with time. The current calibration of the groundwater pathway resulted in a very low sorption coefficient for Ra-226, whereas experimental measurements suggested a higher value, dependent upon solution chemistry. The solution chemistry affects the number of adsorption sites. The experimental measurements indicated that, when the groundwater is rich in calcium sulphate, sodium bicarbonate and other ions, the K_D is low. When the solution composition changes, the number of adsorption sites increase, causing K_D to increase.

What is needed is an adsorption model to reflect the changes in solution chemistry. This was beyond the scope of the current project. The solution chemistry in boxes 6 and 7 change substantially at time of 600 years to reflect the wash out of gypsum, while the solution chemistry of the groundwater pathways from the toe of the dam change much less because they are still rich in calcium and sulphate derived from other tailings zones. Accordingly, K_D was estimated to have a mode of 100 in the tailings for the whole time period. This is an adequate assumption for this study. From a source term perspective, one desires to assign all sorptive capacity to coprecipitation and other mechanisms. The K_D of 100 is reasonable, based upon experimental measurements of tailings. But all such measurements on tailings appear to have been made upon tailings solids containing barite, gypsum and anglesite. Accordingly, the resultant K_D 's represent both reversible sorption and coprecipitation phenomena. Hence, in a model using adsorption and coprecipitation, they cannot be used to estimate K_D , where K_D represents reversible adsorption. Even in leaching pachuca solids well washed to remove gypsum, barite and anglesite, the K_D 's measured were judged to have some coprecipitation occurring due to the further sequestering of barium into the aqueous solids.

Future work is required to define an adequate sorption model, especially for cases where coprecipitation phases are washed out. It needs to be a function of the solution chemistry of the porewater.

5.5 Analysis of Sorption (K_D) and Distribution (Coprecipitation) Coefficients

Previous sections have shown that the calculations of dose rate for potential receptors is influenced in part by the coefficients which control the solid solution distribution of

radionuclides. As well, there is some uncertainty concerning the solid phase controlling Th-230/Th-232 in the tailings. This section summarizes values for sorption and distribution (coprecipitation) coefficients used in this report (Table 5.1), and suggests a direction for future study.

In the geochemical field, and in this report, the terminology "distribution coefficient" is used to describe the linear adsorption coefficient, " K_D ". This coefficient is used in this work for both tailings, the groundwater environment and lakes. In the coprecipitation field, and in this report, the terminology "distribution coefficient" is used to describe the coprecipitation (distribution) coefficient. This coefficient is used in this work for tailings.

The distribution (K_D) coefficients used in this work have a substantive range for different environments, especially for Th-230 (Table 5.1). The range for Ra-226 and Pb-210 is smaller. In contrast, the range used by SENES (1986) is smaller for the three radionuclides. Except for the lake parameters, the major differences in values between environments is that used for the soils and the groundwater pathways. The values used for the soils of this work were taken from measurements made upon glacial tills and locally burrowed fill in the area of the material excavated for the tailings dams. These values are similar in nature to the values used by SENES (1986).

However, when these values were used for calibration of the groundwater model for the pathway through the toe of the dams, the predicted values were too low for the operating period of the tailings. Accordingly, calibration studies were undertaken. The resultant values for K_D were decreased to the values given in Table 5.1 in order to obtain a match between observations and model calculations.

The values used in the groundwater calibration are within the range used in the literature. Accordingly, they are plausible values.

Subsequent calculations with the model, in a walk-through mode, indicate the following (Appendix E, Figures E2.9, E2.10):

- o the long-term calculated activity of Th-230 in groundwater is generally an order of magnitude higher than presently observed in both dams;

TABLE 5.1: ANALYSIS OF DISTRIBUTION COEFFICIENTS USED IN THIS WORK

Environment	Sorption K_D Values (L/kg)		
	Th-230	Ra-226	Pb-210
This Work			
Tailings	C (100)	C (100)	C (100)
Groundwater:			
o South Dam	T (6, 12, 24)	T (4, 7, 10)	T (2, 5, 8)
o North Dam	T (5.5, 11, 22)	T (2, 6, 10)	T (2, 4, 6)
Lake	T (25,000, 50,000, 75,000)	T (100, 200, 300)	T (500, 1,000, 1,500)
Soil	U (2,000, 6,000)	U (9,000, 13,000)	U (5,000, 12,000)
Literature	(10 to 1E7)	(10 to 10,000)	(10 to 5E5)
Measurement on RL Soils	(1,300 to 4,000)	(7,000 to 12,000)	(4,900 to 14,000)
SENES (1986)			
Tailings	0	T (5, 40, 75)	T (20, 60, 100)
Groundwater	N (500)	N (70)	N (670)
Lake	calculated	N (6.5)	N (150)
Soil	N (700)	N (2,200)	N (3,300)
Coprecipitation (Distribution) Coefficients			
Source of Values	D_{Ra-Ca}	D_{Ra-Pb}	D_{Ra-Ba}
This Work	T (20, 50, 75)	T (0.417, 0.687, 1.25)	T (0.086, 0.112, 0.137)
BEAK (1986)	T (250, 800, 1,200)	T (6.67, 11, 15)	T (1.38, 1.8, 2.2)
SENES (1987)	-	-	U (1.8-2.0)

N = nominal value
 U = uniform
 T = triangular
 C = constant

- o the long-term calculated activity of Ra-226 is lower in the north dam, but higher in the south dam, than presently observed; and
- o the long-term calculated activity of Pb-210 is about one-half order of magnitude higher than presently observed in both dams.

The major difference between the calibration conditions and long-term conditions is that the tailings design is changed from short-term water balances (with the mill discharge) to long-term water balances (with the decommissioned design). In fact, analysis of the short-term conditions indicated that the calculated activity of radionuclides starts to increase somewhat at a time point beyond that used for the groundwater path calibration study.

Accordingly, it is suggested that the calibration values obtained in this study for groundwater path K_D values may be low. However, it is doubtful that the calibration would result in values which are close to those measured on the glacial tills without addition of a theory to explain the effect of solution ions upon K_D values.

There is a possible explanation for the lower K_D values used in the calibration based upon competition between different ions for ion exchange sites. Measurements on the Rabbit Lake soils (BEAK, 1987) indicate that the distribution (K_D) coefficient for radium decreased approximately an order of magnitude as the ionic strength was increased approximately two orders of magnitude. The K_D value for thorium was independent of ionic strength. The experiment was made using a sodium bicarbonate salt. This is consistent with more sodium ions in solution competing for ion exchange sites and displacing radium ions. Future work should evaluate the effect of ionic strength and solution ionic composition upon the values of K_D .

Extremely high values have also been measured previously for K_D , particularly in lakes and oceans. Values of the order of 10^5 to 10^7 were typical of oceans (see Snodgrass, 1986). These values are implausible for linear K_D values (i.e., using the one-site binding model type of theory). They are, in fact, more plausible values for coprecipitation or precipitation phenomena. In this case, the solution composition is not controlled by a linear relationship, but rather by a solubility product (for precipitation phenomena), or by another solution ion and the associated solid phase (for coprecipitation phenomena). Further work is required to establish the associated solid phase and the manner that it affects K_D values.

Within the source term, two sets of values of distribution coefficients (D) have been used. Those of BEAK (1986) and SENES (1987) were based upon the inferred values developed by Langmuir and Reise (1985) from the literature. These values are generally from laboratory solutions for precipitating conditions. The values of this study are based upon calibration studies, i.e., selection of distribution coefficient values to obtain a match between model predictions and observations. These calibration studies resulted in a decrease in the distribution coefficients by 16 times. This recalibration allows for more Ra-226 in solution than the values of Langmuir and Reise (1985). The validation study of SENES (Table 5.2) suggested that of the Langmuir and Reise values were reasonable. However, there is considerable scatter in the observed data and they only used one solid phase (barite) whereas BEAK (1986, and this study) used all three solid phases, consistent with the theory developed by Langmuir and Reise.

It is suggested that the recalibration is justified by the fact that conditions in Rabbit Lake tailings are dissolved conditions, whereas the previous values are from laboratory precipitation experiments. Future work in coprecipitation studies should involve the following types of work:

- o field measurements to ascertain that the values obtained previously are accurate;
- o further washing studies to ascertain the kinetics of dissolution of radionuclides from the Rabbit Lake tailings; and
- o laboratory studies to ascertain values for D in pure solution.

Within the source term, there is also a range of values used in UTAP studies for the Th-232 solubility product. The SENES (1986) calibration used a mixed solid which ranged from an amorphous form ($pK_s = -6.3$) to a crystalline form ($pK_s = -1.78$). The recent SENES (1987) work introduced a pH-dependent reaction to account for polymeric forms which probably form in near-neutral conditions. This has the effect of increasing the calculated solution concentration. The assumptions of SENES show some agreement between predictions and observation (Table 5.2), all but the observed range is substantial. In this work, a phase has been assumed based upon calibration studies with observed porewater data. Its solubility product ($pK_s' = 7.93$) emulates that of a well-crystallized solid described by Baes and Mesmer (1976). This form is slightly more crystalline than the amorphous form assumed by SENES (1986) and substantially less

TABLE 5.2: COMPARISON OF OBSERVED AND PREDICTED VALUES FOR LAC NOR TAILINGS

Layer (Depth)	Th-230 (Bq/m ³)		Ra-226 (Bq/m ³)	
	Predicted	Observed*	Predicted	Observed*
L ₂ (0.5 m)	0	1.3-7.0	4.5	2.7-3.4
L ₃ (12 m)	3.1	15-180	4.3	1.5-240
L ₄ (12.75 m)	2.5	0.2-22	4.4	34

* Most frequently observed range.

crystalline than the crystalline (thorianite) form. The assumptions of SENES show some agreement between predictions and observations.

For the Rabbit Lake tailings, more field measurements and solid phase studies would aid in the definition of thorium geochemistry. Priority to porewater measurements would be useful.

5.6 Other Applications of UTAP

The UTAP code has been recently applied to two other applications: part of the EIS analysis for the A,D, and Eagle expansion of the Rabbit Lake mill and to a probabilistic assessment of riverine dissolved oxygen.

The EIS assessment of the mill expansion involved calculation of the concentration of radionuclides (Th-230, Ra-226), stable elements (arsenic, nickel, sulphate, copper, lead, boron, calcium, chloride, potassium, magnesium, sodium, total phosphorus), total inorganic carbon and alkalinity in Hidden Bay and Wollaston Lake. The assessment was made for discharge of treated effluent from the mill with different loadings of substances over time, dependent upon the feedstock to the mill. The major modifications to the UTAP code was input data for mill discharges which varied over time, including only the lake portion of the code in the calculations, and the expansion of the data management structure and lake code to make calculations for the extra substances. All this effort involved a modest amount of professional time for a computer programmer and environmental analyst. Running the code took approximately 5 min of cpu time on the SUN computer for 100 iterations. This is substantially less than the 2.5 hours used for 500 iterations for the full code (source term through to dose calculations).

The second application involved incorporation of a riverine DO model which calculates the non-steady state DO concentration down river of a waste discharge into the UTAP probabilistic framework. The major modifications were to the input data deck and the data management system. The flexible system of input data and the data management structure, and the parameter sampling portions of the code, were left essentially intact. These modifications involved a portion of a week of a programmers time. Computation time was approximately four hours for 25 iterations. The computation time is high due to the numerical solution algorithm of the advection-diffusion equation.

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The probabilistic computer code, UTAP, developed for the National Uranium Tailings Program as a tool for predicting the future dose rate to human populations, was modified and applied to a series of proposed decommissioning designs for the Rabbit Lake tailings management area, located near Wollaston Lake, Saskatchewan. The objective of this study was to investigate the feasibility of modifying the UTAP system model for application to the Rabbit Lake tailings site and to conduct a trial application for evaluating the environmental and dosimetric consequences of different tailings decommissioning options. The tasks associated with this objective are:

- o review and revise, as necessary, existing component models,
- o collect and prepare input data from information available on the Rabbit Lake tailings and the local environment,
- o run UTAP,
- o assess the results, and
- o write a report.

The UTAP code considers the geochemical evolution of U-238 and Th-232 decay series radionuclides in the tailings pile, the transport of these radionuclides through aqueous and atmospheric pathways to potential receptor locations, their accumulation in food, and the associated radiological dose to humans.

The code uses steady-state estimates for the water budget of the tailings and receiving waters for making the calculations, but computes the non-steady state response of the geochemical system of the tailings and the receiving environments of groundwater and surface water. The code does not predict groundwater flow rates or direction in response to variations in precipitation and permeability of the ground; appropriate assumptions or predictions made by more detailed groundwater models such as those which use the finite-difference or finite-element method must be incorporated into the UTAP code.

Two potential receptor locations are considered in the study - one at the Wollaston Lake community and one at the Hidden Bay fishing camp. The Wollaston Lake receptor would



2



be one of the several hundred individuals living year-round on the shore of Wollaston Lake in the town of Wollaston Lake. The Hidden Bay receptor is assumed to be a fishing guide who would live in the camp during summer months and guide fishermen from outside the local area.

The pathways of potential dose considered in this study are inhalation of radon and dust from atmospheric pathways, external exposure to groundshine, drinking of surface water, and consumption of vegetables and berries contaminated by atmospheric dustfall. Unlike other applications of UTAP, consumption of wild animals such as moose and caribou are not considered because these animals are hunted routinely only in areas remote from the Rabbit Lake site, beyond the distance limits of the atmospheric component model.

To calculate dose at these two potential receptor locations, the SENES Phase III code, UTAP.3, was adapted and revised as appropriate. This adapted and revised code was named UTAP.RAB. This study used the basic source term model developed previously by BEAK for non-pyritic, arsenic- and nickel-rich tailings, but modified it to consider new substances (e.g., magnesium), new assumptions (e.g., thorium hydroxide control upon Th-230 dissolution), and a more complex physical representation of the tailings. Physically, differences between zones of fines and coarse material in the Rabbit Lake tailings, the effects of an engineered cover and groundwater cross-flow from the north side through the south side are considered.

The UTAP.3 code for groundwater, atmospheric transport and deposition, and soil was used; the atmospheric transport aspects were changed for computational efficiency to calculate atmospheric concentrations only in sectors containing the potential receptors because foraging wild animals are not considered in this particular application. The BEAK (1986) code for receiving lakes was used due to the embayment characteristics of Hidden Bay connected to Wollaston Lake. The parameter sampling algorithms of UTAP.3 were used; the input data structure of BEAK (1986) was implemented due to the ease of changing the input parameter list, the requirements of the source term, and the plotting graphics.

The model was used to calculate the time trend in committed dose equivalent (herein called 'dose rate') received by an individual at the specified receptor location ("the potential receptor") and concentration of radionuclides in various environmental media

(groundwater pathways, three lakes and various foods, soils). The results are presented both as plots of dose and ambient concentrations over time for four different management scenarios for a concave tailings surface and as a walk-through of calculated radionuclide concentrations in all environments. The four management options considered in this study:

- Case 1: Base case - shaped surface, no cover;
- Case 2: 600 mm sandy till cover, 150 mm topsoil, vegetation;
- Case 3: 600 mm soil-bentonite infiltration barrier, 150 mm topsoil, vegetation;
and
- Case 4: 600 mm waste rock erosion barrier.

This present study has emphasized the following:

- o model application;
- o use of physical detail and finite element modelling to determine subsurface flow pathways through the tailings and surrounding media;
- o sufficient detail on pathways to allow calculation of fluxes of contaminants from the tailings;
- o seven groundwater pathways from the tailings area intersecting with surface water at various distances from the tailings;
- o a source term model configured to described heterogeneity caused by different depositional histories in the tailings pile;
- o coding of these aspects into the UTAP systems code;
- o the incorporation of quality assurance of code testing;
- o the coding of flexibility in the source-term to accommodate such requirements as wide ranging management options and future code modifications;
- o the documentation of all aspects of the study.

To assist this study, several special studies were funded by Eldorado Resources Limited to characterize further the physics and hydrogeology of the tailings and geochemical aspects of the solid-porewater distribution of radionuclides. The studies included:

- o A groundwater flow study;
- o Chemical measurements of tailings porewater;
- o Mineralogy and solid phase identification of tailings solids;
- o A chemical washing study;
- o A Ra-226 nuclear emulsion study; and
- o Adsorption (K_d) measurements upon geological materials of receiving groundwater environments.

These studies have been carried out in parallel with the work of this project. Results from these studies available at the end of February 1986 have been incorporated into the modelling work of this project. The results of these studies are incorporated into BEAK (1987) as a separate report to Eldorado Resources Limited.

This modelling application has addressed several unique features of the Rabbit Lake tailings site. These include:

- o the use of seven boxes in the source term to account for vertical and horizontal variability caused by tailings disposal;
- o the consideration of physical and chemical differences in the coarse and fine fractions within the tailings;
- o consideration of a permafrost zone in the tailings;
- o provision for seven groundwater pathways which emerge to surface at different distances from the tailings and in three directions from the tailings;
- o model calibration using laboratory measurements for the linear distribution coefficient, and observed aqueous concentrations in the tailings porewater and in seepage from the dams; and
- o the hydrologically-coupled nature of Hidden Bay and Wollaston Lake.

6.2 Concluding Statements

The following general statements result from this work.

1. The general systems model (UTAP) can be readily adapted for application to actual tailings management areas.

2. This application requires a knowledge of, or collection of, site specific data; and a modification of UTAP component models to reflect these site specific characteristics.
3. The use of the UTAP system model for a site specific application can have two general types of objectives:
 - a primary one for which it was designed;
 - a) Evaluation and optimization of a series of sets of management options for long term management.
 - and a secondary one;
 - b) Evaluation of the effects of operational releases on the natural environment and receptor groups for which probabilistic estimates of environmental concentration or dose rate are desired.

This secondary objective was used in conjunction with calibration studies of particular model coefficients (tailings and groundwater distribution coefficients) for use in the primary objective a) using short term monitoring data as the database. UTAP was also modified to evaluate the effect of operational releases upon the receiving lakes in another allied study.

Specific application of UTAP to the Rabbit Lake tailings site has demonstrated the following:

1. The geometric mean dose rate for both the Hidden Bay and Wollaston Lake receptors is calculated to be approximately constant for the first several hundred years for the base case. The dose rate increases by approximately three to four times at 600 years in the future. This increase results from washout of the mineral phase controlling Ra-226 in a portion of the tailings directly adjacent to the south dam.
2. The main pathways for radionuclide impact are consumption of fish and drinking water. The impact of airborne pathways is over two orders of magnitude lower. Of the airborne-associated routes, radon dose is generally larger than dust inhalation, groundshine, or vegetable plus berry consumption.
3. Pb-210 generally makes the largest contribution to dose, followed by Ra-226. The dose rates for Th-230, total U and Po-210 are similar to or slightly less than those attributed to the other two nuclides.

4. The geometric mean dose rate for the Hidden Bay receptor is slightly larger than, but close to, the dose rate for the Wollaston Post receptor. This results from the aqueous concentrations of nuclides in Hidden Bay being only slightly higher than those of Wollaston Lake due to exchange flow between the bay and the lake.
5. The effects of various covers as management options have a negligible effect upon calculated dose because the covers mainly affect atmospheric transport, while the main contributing pathways are aquatic.

Values of the dose rate for the two receptors, which are of the order of 1 to 10 uSv/year, are given in previous chapters, and a comparison of this dose rate is given with that from natural sources. Care should be taken in quoting these values with much veracity because the calibration used in the model requires further study. In particular, the calibration for the mechanisms controlling Th-230, Ra-226 and Pb-210 in the source term and in the groundwater pathways should be checked with additional field data. Further calibration studies may result in different dose estimates being calculated. However, the results of this study have fulfilled one objective of this work - to use the study to demonstrate the application of UTAP and to provide direction for any further work.

6.3 Recommendations

The following general recommendations result from this work.

The UTAP system code should be appropriate for most applications to other tailings management areas in Canada. In future applications;

1. The component models should be scrutinized for site specific applicability with order of priority being:
 - a) coding within the source term model (e.g., geochemical mechanisms; tailings heterogeneity; groundwater flow pathways);
 - b) coding which directs the routing of water transport of contaminants between source and receptor, the sequence of groundwater and surface water pathways;
 - c) component pathway model.
2. Input data for use in UTAP component models should be site specific wherever possible and supplemented by literature data only as necessary.

Application of the UTAP system code to the Rabbit Lake Tailings points out the need for additional fundamental experimental studies, field measurements, and modelling studies to confirm key assumptions used in this work. They include the following:

1. A model is required to predict the adsorption coefficient for Ra-226 in geological materials as a function of ion exchange and solution composition.
2. Additional experimental measurements are required to explain the calibration obtained for the K_D in this study for radionuclides such as Ra-226. These additional measurements would provide data for development of the ion exchange model described above, and confirm the calibration used for tailings grains, geological materials adjoining the tailings area, water column particulates in Hidden Bay and Wollaston Lake, and soils associated with the vegetable garden.
3. Additional measurements of thorium chemistry in porewater and tailings solids and mineralogical studies are required:
 - o to measure the ratios of Th-230 and Th-232 in both porewater and the solid phase;
 - o to confirm the existence of a Th-232 oxide phase of some degree of crystallinity which controls Th-230 activity; and
 - o to define the solubility product of the Th-232 phase.
4. Additional groundwater studies would be useful to evaluate the long-term water levels, groundwater flow pathways, and groundwater flow rates developed for this study.
5. Additional field data would allow further checking of the model. These include the following:
 - o additional porewater measurements of Pb, SO_4 , Pb-210 and Ra-226 to allow evaluation of the calibration of this model. In particular, the calibration of Ra-226 needs additional checking;
 - o measurements of dissolved organic carbon in the tailings porewater to confirm the potential role of organic carbon in controlling redox reactions in the near-term;
 - o development of titration curves of the tailings porewater and solid phases to confirm buffering systems (e.g., carbonate, and not ammonium) assumed in this work; and
 - o environmental measurements of Th-230 and Th-232 in Wollaston Lake to evaluate ambient levels.

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APPENDIX A

Study Terms of Reference

1550. 23317-6-1729 1550. 23317-6-1729	1550. 23317-6-1729 1550. 23317-6-1729
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APPENDIX "I"

STATEMENT OF WORK

APPLICATION OF THE NATIONAL URANIUM TAILINGS PROGRAM
PROBABILISTIC SYSTEM MODEL (UTAP) TO
THE RABBIT LAKE URANIUM TAILINGS SITE

BACKGROUND

The probabilistic system model developed to assess the impact of various disposal technologies for uranium mill tailings has been applied to hypothetical sites so far. That is, the emphasis to date has been on the overall system modelling approach with application to hypothetical sites as a demonstration of the approach. The system model (UTAP) is in its last phase of development. Component models have been developed that are descriptive for low-grade, pyritic ores, typical of the Elliot Lake region of Ontario, and higher-grade, non-pyritic ores with significant levels of arsenic and nickel, typical of some Saskatchewan ores.

To demonstrate the usefulness of the methodology requires application to real sites. Application to a specific site requires much data for the site and system component models that are descriptive of the site characteristics. Based on a recommendation from the NUTP's Technical Advisory Committee, the Rabbit Lake uranium tailings site in Saskatchewan has been chosen as one of two demonstration sites. The purpose of this project is to show the use of UTAP for a real site, and not provide a full assessment for licensing purposes. The level of modelling detail will need to be finalized after contract award.

This project is being co-sponsored by the NUTP and Eldorado Resources Limited (ERL). The specific work requirements given below are the complete requirements to be performed by ERL and the NUTP contractor, in concert, according to the split given below. NUTP will administer the contract.

OBJECTIVE

The objective of this contract is to develop a system model for the Rabbit Lake uranium tailings site and apply it. In brief, the tasks are:

1. review and revise, as necessary, existing component models,
2. collect and prepare input data,
3. run UTAP,
4. assess the results, and
5. write a report.

SPECIFIC REQUIREMENTS

To achieve the objective the following tasks will be performed:

- Task 1: (a) Develop the system model for Rabbit Lake uranium tailings. This entails reviewing the existing component models for applicability to the Rabbit Lake site, and modifying them as necessary to describe the site characteristics. These characteristics include the tailings' constituents and natural processes occurring in the tailings, contaminant transfer along pathways from tailings to man, critical group receptors, and any other site peculiarity which can affect the environmental impact from the tailings. Some existing component models (e.g. dose calculations) may be adopted as they are, others (e.g. source term) may require wholesale changes or complete re-development, or new component models (e.g. new pathways) may be required.

Changes require development of model specifications, development of the model, coding, and code testing. Finally, the component models are integrated into the system model, and the new system model tested. The whole process is governed by a quality assurance (Q.A.) program that ensures careful development and testing of the system model produced.

ERL will perform the component model reviews and specification of new models required with help from the contractor for the source term model. The contractor will code the new models, test them, and integrate them into and test the new system model. The contractor is responsible for the Q.A. function.

- (b) ERL will determine and specify which disposal options are to be studied. The emphasis is on showing UTAP's ability to distinguish between various options, and not on a final assessment of the Rabbit Lake tailings close-out. The contractor will incorporate the chosen options into the system model. To keep the scope of work practical, two or three options should be chosen.

Task 2: Develop the input data for the Rabbit Lake version of UTAP. This involves collection of site-specific data, and depends on the requirements of the system model developed in Task 1. In some cases, site-specific data may not be available. Then, the best available literature data is used or site measurements could be made. Once the raw data is collected, it must be transformed into input data for the computer code. Many input parameters require development of a probabilistic density function. ERL will be responsible for collecting the data. The contractor will prepare the code input data.

Task 3: Run the Rabbit Lake version of UTAP developed in Task 1 with the data developed in Task 2. The contractor will perform this task.

Task 4: Assess the UTAP results from the runs in Task 3. The numerical results from UTAP must be explained in terms of not only what the numbers say, but why. The important results must be selected, as well as how they are to be presented. This task will be performed jointly by ERL, NUTP, and the contractor.

Task 5: Write a report. The report will describe the model and input data development and the assessment results. Any major observations on the application of UTAP to a real site plus any recommendations (such as level of modelling detail, data collection) for future applications will be given.

Initial drafting of the report sections will be split between ERL and the contractor according to the split described in Tasks 1 to 4. The contractor will have the responsibility of assembling the report. Review of the report will be done by ERL and NUTP, with subsequent revisions by the appropriate organization. It will be issued as an NUTP report.

A summary of work responsibilities is given in the accompanying table.

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WORK SPLIT FOR APPLICATION OF UTAP

to the

RABBIT LAKE TAILINGS

ERL is Eldorado Resources Limited

NUTP is the National Uranium Tailings Program

C is the contractor

Task	Responsibility			
	Component Model	Rev./Re-spec.	Code	Test & QA
1. Develop system model (review and revise component models)	Source term	ERL/C	C	C
	Surface water	ERL	C	C
	transport			
	Groundwater	ERL	C	C
	transport			
	Atmospheric	ERL	C	C
	dispersion			
	Biological transfer	ERL	C	C
	- aquatic			
	- terrestrial			
	Uptake by man	ERL	C	C
	Disposal options	ERL	C	C
2. Data development	Collect site-specific data - ERL			
	Prepare code input data - C			
3. Run the code	C			
4. Assess results	ERL/NUTP/C			
5. Write report	Prepare draft - ERL/C			
	Review - ERL/NUTP			
	Revise - ERL/NUTP/C			

APPENDIX B

"Steady" and "Aquifer" Simulations

APPENDIX B: "Steady" and "Aquifer" Simulations

Initial attempts (Eldorado, pers. comm.) were made to estimate the long-term water level of the tailings under a decommissioned design. Using data from monitoring wells, the inferred hydraulic characteristics of the tailings were described by a model of the form:

$$\Delta H = K \cdot Q$$

where: Q is the total flow infiltrating the tailings,
 ΔH is the change in piezometric level of the groundwater, and
 K is the calibration constant and an overall effective permeability coefficient.

The observed data used for calibration were from wells which showed year-to-year variations of the order of 1 m. The flow rate data were during the mill discharge.

For the long-term water levels, the piezometric level was calculated to be in excess of 15 m below the tailings surface using this relationship for an inflow (Q) which is an order of magnitude less than during operations. This is judged to be inappropriate and to result from calibration of the relationship for the most hydrologically active (surficial) component of the tailings.

Two finite element codes, written by professional staff at the University of Waterloo, were run to assess the long-term water levels of the tailings. The simulations are summarized in BEAK (1987). Pertinent results are summarized here.

The two codes are "STEADY" and "AQUIFER". "Steady" is a steady-state, 2-D code for calculating water levels in a vertical section. "AQUIFER" is a 2-D, non-steady-state code for calculating the water levels for a horizontal section given horizontal inflows, net infiltration and water withdrawal or surcharging at well points. "STEADY" was used to estimate the water levels under a decommissioned design and flow rates along different groundwater pathways.

"AQUIFER" was used to determine the time response of the regional and tailings groundwater system to the cutoff of discharge to the Rabbit Lake tailings pond.

Simulations from runs of "STEADY" indicated the following:

- o for the measured permeabilities (Geocon, 1986), the hydrological flow (estimated by Geocon, 1986) into the tailings is too large;
- o for the water balance during operating conditions (Table 3.2.1), the permeability of the tailings must be larger; and
- o using measured permeabilities and the long-term flow balance, the depth of the unsaturated zone is in excess of 10 m, consistent with the simple hydraulic flow - head calculations.

Accordingly, a plausible case for actual permeabilities and the long-term flows was estimated and tested in a sensitivity run (BEAK, 1987).

Analysis with "AQUIFER" indicates that the change in head due to a change in pumping rate is almost complete in one to four years dependent upon conditions simulated. This fast response results from calibration of the model to the hydrologically active surface areas and to the resistance effects of deeper groundwater strata. It suggests that assumption of steady-state water levels in UTAP for a 5-, 10- or 25-year time step is quite appropriate.

APPENDIX C

Detailed Aspects of Source Term Chemistry

APPENDIX C: DETAILED ASPECTS OF SOURCE TERM CHEMISTRY

C.1 Evaluation of Primary Minerals and Secondary Precipitates in the Source Term

C.1.1 Sampling Procedures

A series of porewater samples were obtained from the Rabbit Lake uranium mill tailings from two piezometers installed previously by GEOCON and two well points inserted by us 1 m below the tailings surface. A quality assurance program involved some samples (1 of 20) split externally, samples analyzed in duplicate by the laboratory and anion-cation balance. Sample splitting resulted in sample sizes varying from 100 mL to 8 L.

The analytical approach used was to analyze one set of samples (from one piezometer) with a sufficient volume (8 L) such that all anions, cations and radionuclides could be measured. This allowed one to determine levels, required detection limits and sample sizes required for the other samples. The first set required most of the 8 L volume for sample preparation because of kerosene and ethylene glycol present in the sample. The kerosene was discharged by the mill (kerosene is the carrier for the IX solvent). The ethylene glycol was added between successive samplings of the piezometer to prevent the porewater from freezing and to allow the porewater to rebound.

The results from the first analysis indicated that all of the samples externally split and that the daily samples from the same piezometer, which were submitted as separate samples, were too small in volume. Accordingly, they had to be combined into one sample. This resulted in the quality assurance program being limited to duplication of the same sample within the laboratory and anion/cation balances.

The internal duplication shows reasonably good agreement (see Table C1.1). The anion/cation balances also agree reasonably well, with the majority of electroneutrality being explained by calcium, magnesium, sulphate and bicarbonate (alkalinity).

C.1.2 Equilibrium Calculations

Several of the water samples were analyzed with an equilibrium chemistry computer code (MINTEQ; Felmy *et al.*, 1984). Representative results are given in Table C1.2 for

TABLE C1.1: RESULTS OF INTERNAL LABORATORY DUPLICATION

Constituent*	Sample Number		
	21597	21603	21604
Major Constituents (mg/L)			
Ca	395	366	429
Ca-D	388	-	-
K, flame	99	174	13
K, flame-D	101	not required	16
Mg, titr	1,020	1,990	1,240
Mg, titr-D	1,041	not required	1,230
Trace Constituents (mg/L)			
B, ICP-AES	25	43	0.41
B, ICP-AES-D	28	52	0.46
P, ICP-AES	16	8.8	1.7
P, ICP-AES-D	18	10	2.0
Trace Metals (mg/L)			
Ag, ICP-AES	L 0.005	L 0.005	L 0.005
Ag, ICP-AES-D	L 0.005	L 0.005	L 0.005
Al, ICP-AES	0.84	0.71	1.4
Al, ICP-AES-D	1.0	1.0	1.5
Ba, ICP-AES	0.031	0.017	0.034
Ba, ICP-AES-D	0.035	0.019	0.036
Be, ICP-AES	L 0.005	L 0.005	L 0.005
Be, ICP-AES-D	L 0.005	L 0.005	L 0.005
Cd, ICP-AES	L 0.005	L 0.005	L 0.005
Cd, ICP-AES-D	L 0.005	L 0.005	L 0.005
Co, ICP-AES	L 0.005	L 0.005	L 0.005
Co, ICP-AES-D	0.007	L 0.005	L 0.005
Cr, ICP-AES	0.039	0.066	0.053
Cr, ICP-AES-D	0.040	0.060	0.053
Cu, ICP-AES	0.022	0.010	0.012
Cu, ICP-AES-D	0.034	0.021	0.018
Fe, ICP-AES	0.95	0.50	0.72
Fe, ICP-AES-D	1.1	0.60	0.73
Mn, ICP-AES	1.5	0.84	1.8
Mn, ICP-AES-D	1.9	1.20	1.9

TABLE C1.1: RESULTS OF INTERNAL LABORATORY DUPLICATION

Constituent*	Sample Number		
	21597	21603	21604
Mo, ICP-AES		4.4	1.2
Mo, ICP-AES-D		5.1	1.1
Ni, ICP-AES		0.016	0.097
Ni, ICP-AES-D		0.025	0.11
Pb, ICP-AES		L 0.02	L 0.02
Pb, ICP-AES-D		L 0.02	L 0.02
Si, ICP (soluble)		9.9	3.5
Si, ICP (soluble)-D		11	4.2
Ti, ICP-AES		0.009	L 0.005
Ti, ICP-AES-D		0.009	L 0.005
V, ICP-AES		0.23	0.26
V, ICP-AES-D		0.29	0.28
W, ICP-AES		L 0.02	L 0.02
W, ICP-AES-D		L 0.02	L 0.02
Zn, ICP-AES		L 0.005	L 0.005
Zn, ICP-AES-D		L 0.005	L 0.005
Radionuclides (Bq/L)			
Pb-210, total		6.0	1.4
Pb-210, total-D		not required	1.3
Ra-226, total		2.5	2.5
Ra-226, total-D		2.5	3.0
Th-228, total		0.09	0.10
Th-228, total-D		0.06	0.06
Th-230, total		0.8	1.1
Th-230, total-D		0.8	1.3
Th-232, total		0.06	0.14
Th-232, total-D		0.05	0.13
U, total (ug/L)		8,200	1,600
U, total-D (ug/L)		8,100	1,500

* "D" on a parameter means duplicate.

"L" on a parameter value means less than.

one water sample. The results are given in terms of the log of the saturation index assuming that the water temperature is 4°C (Table C1.2a) and 15°C (Table C1.2b) for water sample 21593 (Piezometer M1, 05-06 November sample) and 4°C (Table C1.3) for water sample 21596 (Piezometer S1, 05-06 November sample). The saturation index (SI) is the ratio of the ion activity product and the solubility constant. If the solution is supersaturated with respect to a mineral phase, the log (SI) will be larger than zero. If the solution is undersaturated, the log (SI) will be less than zero.

The results are given in terms of the log of the saturation index. The log of the solubility constant for the appropriate mineral phase, and the log of the ion activity product are also given for each mineral phase. The solubility constant is reported to allow the reader to critique the thermodynamic database. The database used is one compiled for mineral phases, which was originally used in WATEQF and recently updated. However, this does not guarantee that all thermodynamic databases are internally consistent, a need which is evolving (see Appendix A, BEAK, 1986 for further details with respect to the need for an internally consistent, thermodynamic data base).

The calculations indicate that the porewater is substantially over- or under-saturated with respect to most mineral phases. A log of SI greater than one or less than one is reasonable grounds for making this assessment on a first-cut basis. The phases anhydrite (CaSO_4), aragonite (CaCO_3), calcite (CaCO_3), dolomite (Mg,CaCO_3), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), magnesite (MgCO_3), aluminum hydroxide (Al(OH)_3) and aluminum hydroxide sulphate (Al(OH)SO_4) are within the range where they are reasonably close to saturation. Calculations for 4°C and 15°C change the calculations for SI by small amounts relative to the range of SI values for the different phases.

For minerals of interest to this study, the calculations provide some justification for the assumptions used in the source model, but also require interpretation. The model assumes that gypsum is the phase controlling calcium and sulphate equilibrium in the tailings porewater, whereas the saturation calculations indicate that either gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4 , a non-hydrated form) were equally plausible solid phases. In fact, anhydrite is calculated to be closer to saturation than gypsum at 15°C, but is further from saturation at 4°C for water samples labelled 21593. Similarly, anhydrite is further from saturation than gypsum at 4°C in water sample 21596. In all cases, the porewater is under-saturated with respect to anhydrite and saturated with respect to gypsum.

TABLE C1.2a: SATURATION INDEX CALCULATIONS FOR RABBIT LAKE
POREWATER 21593 (MI, 05-06 November; 4°C used as ambient
temperature)

SATURATION INDICES FOR ALL MINERALS AND SOLIDS

NAME	SAT INDEX	LOG K	LOG IAP
ALOH3(A)	0.027	-11.882	11.909
ALOH5O4	-0.358	3.230	-3.588
AL4(OH)10SO4	9.439	-22.700	32.139
ALLUM K	-9.178	5.571	-14.749
ALLUNITE	10.645	1.564	9.082
ANHYDRITE	-0.110	4.428	-4.538
ARAGONITE	-0.419	8.167	-8.586
ARTINITE	-7.562	-11.196	3.634
BOEHMITE	1.770	-10.140	11.910
BRUCITE	-6.636	-18.227	11.591
CALCITE	-0.191	8.395	-8.586
DIASPORE	3.669	-8.241	11.910
DOLOMITE	-0.000	16.540	-16.540
EPSOMITE	-1.616	2.297	-3.913
FERRIHYDRITE	2.901	-4.891	-7.792
FE(OH)2.7CL.3	8.052	3.040	5.012
FE2(SO4)3	-37.769	-6.863	-30.906
GIBBSITE (C)	1.873	-10.036	11.909
GOETHITE	6.489	-1.304	7.793
GYPSUM	0.095	4.634	-4.540
HALITE	-6.250	-1.531	-4.719
HEMATITE	17.883	2.295	15.588
HUNTITE	-3.910	28.537	-32.448
HYDRMAGNES'IT	-14.362	5.866	-20.229
JAROSITE NA	6.124	9.191	-3.067
JAROSITE K	9.794	13.063	-3.269
JAROSITE H	1.418	9.037	-7.619
MAGHEMITE	9.202	-6.386	15.588
MAGNESITE	-0.268	7.686	-7.954
MIRABILITE	-4.239	2.168	-6.408
NATRON	-8.271	2.185	-10.456
NESQUEHONITE	-2.658	5.299	-7.957
THENARDITE	-6.250	0.147	-6.397
THERMONATR	-10.727	-0.281	-10.447
PYROCROITE	-7.938	-16.343	8.404
RHODOCHROSIT	-0.847	10.295	-11.141
MNCL2, 4H2O	-11.882	-1.745	-10.137
MNSO4	-10.621	-3.529	-7.093
NICO3	-6.497	6.288	-12.785
NI(OH)2	-2.349	-9.109	6.760
NI4(OH)6SO4	-20.455	-32.000	11.545
BLUNSENITE	-7.017	-13.778	6.761
RETGERSITE	-6.642	2.101	-8.743
MORENOSITE	-6.221	2.523	-8.744
LIME	-24.406	-35.366	10.960
PORTLANDITE	-13.420	-24.379	10.959
PERICLASE	-11.925	-23.517	11.592
SPINEL	-5.867	-41.281	35.414
MAG-FERRITE	6.714	-20.466	27.180
LEPIDOCROCIT	6.422	-1.371	7.793
BASALUMINIT	9.439	-22.700	32.139

TABLE C1.2b: SATURATION INDEX CALCULATIONS FOR RABBIT LAKE
POREWATER 21593 (MI, 05-06 November; 15°C used as ambient
temperature)

SATURATION INDICES FOR ALL MINERALS AND SOLIDS

NAME	SAT INDEX	LOG K	LOG IAP
ALOH3(A)	0.816	-11.068	11.886
ALOH5O4	-0.394	3.230	-3.624
AL4(OH)10SO4	9.335	-22.700	32.035
ALUM K	-9.450	5.354	-14.804
ALLUNITE	10.427	1.446	8.981
ANHYDRITE	-0.027	4.541	-4.568
ARAGONITE	-0.219	8.250	-8.469
ARTINITE	-6.592	-10.331	3.739
BOEHMITE	2.594	-9.294	11.887
BRUCITE	-5.872	-17.449	11.577
CALCITE	-0.046	8.423	-8.469
DIASPORE	4.388	-7.500	11.887
DOLOMITE	0.485	16.789	-16.304
EPSOMITE	-1.729	2.212	-3.941
FERRIHYDRITE	2.900	-4.891	7.791
FE(OH)2.7CL.3	8.050	3.040	5.010
FE2(SO4)3	-36.032	-5.084	-30.948
GIBBSITE (C)	2.536	-9.350	11.886
GOETHITE	6.924	-0.868	7.792
GYPSUM	0.056	4.627	-4.570
HALITE	-6.281	-1.559	-4.722
HEMATITE	18.809	3.223	15.586
HUNTITE	-2.660	29.313	-31.973
HYDRMAGNESIT	-12.328	7.438	-19.766
JAROSITE NA	7.180	10.280	-3.099
JAROSITE K	10.700	14.004	-3.304
JAROSITE H	3.048	10.697	-7.649
MAGHEMITE	9.200	-6.386	15.586
MAGNESITE	0.038	7.872	-7.835
MIRABILITE	-4.829	1.597	-6.426
NATRON	-8.616	1.712	-10.327
NESQUEHONITE	-2.364	5.474	-7.838
THENARDITE	-6.251	0.164	-6.416
THERMONATR	-10.514	-0.196	-10.318
PYROCROITE	-7.283	-15.663	8.380
RHODOCHROSIT	-0.674	10.357	-11.031
MNCL2, 4H2O	-12.431	-2.268	-10.164
MNSO4	-10.193	-3.063	-7.130
NICO3	-6.158	6.587	-12.746
NI(OH)2	-3.360	-10.025	6.666
NI4(OH)6SO4	-20.847	-32.000	11.153
BUNSENITE	-6.392	-13.058	6.667
RETGERSITE	-6.783	2.068	-8.851
MORENOSITE	-6.417	2.435	-8.852
LIME	-23.031	-33.974	10.943
PORTLANDITE	-12.514	-23.456	10.942
PERICLASE	-10.851	-22.429	11.578
SPINEL	-3.245	-38.599	35.354
MAG-FERRITE	8.704	-18.460	27.164
LEPIDOCROCIT	6.421	-1.371	7.792
BASALUMINIT	9.335	-22.700	32.035

TABLE C1.3: SATURATION INDEX CALCULATIONS FOR RABBIT LAKE
POREWATER 21596 (SI, 05-06 November; 4°C used as ambient
temperature)

SATURATION INDICES FOR ALL MINERALS AND SOLIDS			
NAME	SAT INDEX	LOG K	LOG IAP
ALOH3(A)	-0.168	-11.882	11.714
ALOH5O4	-0.565	3.230	-3.795
AL4(OH)10SO4	8.647	-22.700	31.347
ALLUM K	-10.632	5.571	-16.203
ALLUNITE	8.800	1.564	7.236
ANHYDRITE	-0.182	4.428	-4.609
ARAGONITE	-0.956	8.167	-9.123
ARTINITE	-8.044	-11.196	3.153
BOEHMITE	1.575	-10.140	11.715
BRUCITE	-6.638	-18.227	11.589
CALCITE	-0.728	8.395	-9.123
DIASPORE	3.474	-8.241	11.715
DOLomite	-1.017	16.540	-17.557
EPSOMITE	-1.630	2.297	-3.926
FERRIHYDRITE	2.590	-4.891	7.481
FE(OH)2.7CL.3	7.563	3.040	4.523
FE2(SO4)3	-38.429	-6.863	-31.566
GIBBSITE (C)	1.678	-10.036	11.714
GOETHITE	6.178	-1.304	7.482
GYPsum	0.023	4.634	-4.611
HALITE	-7.162	-1.531	-5.631
HEMATITE	17.260	2.295	14.965
HUNTITE	-5.887	28.537	-34.424
HYDRMAGNESIT	-16.283	5.866	-22.150
JAROSITE NA	4.843	9.191	-4.348
JAROSITE K	7.599	13.063	-5.464
JAROSITE H	0.460	9.037	-8.577
MAGHEMITE	8.579	-6.386	14.965
MAGNESITE	-0.747	7.686	-8.434
MIRABILITE	-4.893	2.168	-7.062
NATRON	-9.390	2.185	-11.575
NESQUEHONITE	-3.137	5.299	-8.436
THENARDITE	-6.906	0.147	-7.053
THERMONATR	-11.848	-0.281	-11.567
PYROCROITE	-7.846	-16.343	8.497
RHODOCHROSIT	-1.232	10.295	-11.526
MNCL2, 4H2O	-12.969	-1.745	-11.225
MNSO4	-10.541	-3.529	-7.013
NICO3	-6.662	6.288	-12.950
NI(OH)2	-2.036	-9.109	7.073
NI4(OH)6SO4	-19.218	-32.000	12.782
BUNSENITE	-6.705	-13.778	7.074
RETGERSITE	-6.341	2.101	-8.442
MORENOSITE	-5.919	2.523	-8.443
LIME	-24.466	-35.366	10.901
PORTLANDITE	-13.479	-24.379	10.900
PERICLASE	-11.927	-23.517	11.590
SPINEL	-6.260	-41.281	35.021
MAG-FERRITE	6.088	-20.466	26.554
LEPIDOCROCIT	6.111	-1.371	7.482
BASALUMINIT	8.647	-22.700	31.347

However, these calculations are not sufficient themselves to establish that gypsum is the controlling phase due to uncertainties in the data and due to the need for solid phase identification. One method for assessing uncertainties in the data is the anion-cation balance. The speciated charge balance does not balance respectively by 5.3%, 5.6% and 5.6% for 21596 (4°C), 21593 (4°C) and 21593 (15°C). The anion sum is larger than the cation sum in all cases, by the percentages indicated. These differences are quite reasonable, although imbalances of 2% or less are desirable. Most of these uncertainties must be associated with values for calcium, magnesium and sulphate because these are the dominant ions. An error of 5% in sulphate being too high would decrease the SI, making the porewater quite close to saturation with respect to gypsum.

Solid phase analysis has identified the presence of bassinite ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$) in tailings samples dried at 105°C and gypsum in air-dried tailings samples, but have not identified anhydride.

The kinetics of gypsum dissolution and precipitation (BEAK, 1985) are sufficiently fast (of the order of minutes to hours) that the porewater should be close to equilibrium with gypsum.

Accordingly, it is concluded that the porewater is at equilibrium with gypsum and that the small degree of supersaturation (0.053, 0.023 and 0.095 at 4°C, 4°C and 15°C respectively) represent uncertainties in the porewater analysis. There are small uncertainties also associated with the thermodynamic data for gypsum, but these are judged to be somewhat smaller than those associated with the analytical results. It is also probable that 4°C rather than 15°C is a better descriptor of this data as the porewater was less than 4°C near the surface of the tailings. The temperature of lower levels is unknown, although 4°C is probably a good estimate of the temperature of the level.

For pH control, the saturation calculations indicate that aragonite and calcite as mineral phases of calcium carbonate and dolomite and magnesite as mineral phases of magnesium carbonate are the most probable minerals influencing pH. This results from the role that the carbonate buffering system plays in controlling the pH. Ammonia could play a role, but the pH must be near to 9 for this effect to be significant. Also, the ammonia concentrations must be in the range of 0.01 M (140 mg/L ammonia as N) for its buffering

system to be more influential than that of carbonate. Ammonia data were not determined because of the interference with other porewater constituents (ethylene glycol, kerosene). However, it is judged that the carbonate system would govern the pH of the Rabbit Lake porewater.

The saturation calculations indicate that the porewater is under-saturated with respect to both aragonite and calcite. The porewater is closer to saturation conditions with respect to calcite than aragonite. The solid phase identification did not establish the presence of calcite or aragonite, but it is probable that, with the small amounts of calcite present, the solid phase techniques would not identify these minerals. The unit cell formula of aragonite and calcite are similar, but the crystal structure is different. Because aragonite is a mineral which forms (Plummer and Sandquist, 1982), it is assumed that small amounts of calcite in the lime added to the mill together with tailings reactions make the porewater at equilibrium with calcite. Thus, the pH of the porewater is assumed to be controlled by calcite and then by the metal hydroxide buffering system as defined previously (BEAK, 1986). The magnesium content of porewater is defined by the magnesite solubility relationship and any solution complexation (e.g., sulphate, etc.).

Other minerals of interest include aluminum and iron solids. The calculations indicate that the porewater is essentially at saturation with respect to amorphous aluminum hydroxide for 21593 (4°C) and somewhat more under-saturated with respect to amorphous aluminum hydroxide for 21596 (4°C). It is substantially super-saturated with respect to gibbsite, suggesting that the amorphous form is the most probable aluminum phase present as a secondary precipitate. This justifies the assumption of aluminum hydroxide as the controlling phase in the tailings. However, all iron minerals, including goethite (FeOOH), are substantially beyond the reasonable range for saturation conditions. Even if the amorphous form (Fe(OH)_{3(s)}) is evaluated, the solubility constant only changes by 500 times, leaving the porewater four orders of magnitude super-saturated. One plausible explanation for iron is the formation of colloidal iron particles (e.g., 100 to 200 Å in diameter) which move with porewater and are collected as a "dissolved phase". Another plausible explanation is the existence of reducing conditions in which Fe(II) is present - under such conditions, the "dissolved concentration" of iron is higher in its reduced state than oxidized state for many minerals.

With respect to other mineral phases, aluminosilicates can be expected to be a major source of elements such as aluminum, potassium, sodium and magnesium if they dissolve. These minerals are not extensively evaluated in the calculations. However, their dissolution is usually controlled kinetically, and the kinetics are generally slow (BEAK, 1985). Accordingly, it is probable that these minerals would supply a small, residual amount of ions to the tailings porewater. The significance of this supply over geochemical time scales awaits future evaluation. Its implications are related mainly to the role that these minerals play when secondary precipitates formed in the mill are completely dissolved and hence when new solid phase buffering systems begin to control pH. Its implications also relate to the role that these minerals play in supplying adsorption sites over time and the need to develop models which describe the change in such adsorption characteristics over time.

C.2 Mineralogical Analysis of Rabbit Lake Tailings

Three samples were analyzed mineralogically by X-ray diffraction, Scanning Electron Microscope Examination (SEM) and by washing studies. The data are given in BEAK (1987). The washing solutions were analyzed for Ca, Mg, Si, Al, SO_4 , Fe, Ni, As, Cu, Pb and Zn. The results indicate that less than 4 ppm of the following metals dissolved: Cu, Ni, Pb, Zn, Al and As. Less than 0.07% Si was dissolved. The results for the remaining elements are:

<u>Sample No.</u>	<u>Ca (%)</u>	<u>Mg (%)</u>	<u>Fe (ppm)</u>	<u>SO_4 (%)</u>
1	5.3	0.30	72	12.7
10	2.3	0.19	47	5.5
15	3.0	0.18	29	7.2

Other analyses give the following estimated percent of bassanite, gypsum, quartz, chlorite and illite in the three samples:

<u>Sample No.</u>	<u>Bassanite</u>	<u>Gypsum</u>	<u>Quartz</u>	<u>Chlorite</u>	<u>Illite</u>	
1	16	-	20	60	4	= 100%
10	8	-	25	62	5	= 100%
15	-	11	29	58	2	= 100%

A hypothesis for the presence of bassanite is presented in BEAK (1987).

APPENDIX D

Detailed Aspects of Environmental Pathways

APPENDIX D: DETAILED ASPECTS OF ENVIRONMENTAL PATHWAYS

D.1 Atmospheric Data

D.1.1 General

The highest twenty-four hour rainfall volumes occur in the months of July and August. The greatest amount of precipitation received, in the form of rainfall over a 24-hour period has been recorded as 54.1 mm (2.13 in) in the month of August. Rainfall intensity-duration frequency data have been calculated for the Collins Bay station.

Persistent, long-term, clean snow cover will result in an increase in surface albedo which could result in an increase in the frequency of ground-based inversions. Snow is also a good insulator and influences soil freezing and thawing cycles. Continuous snow cover typically exists at Collins Bay between 15 October and 6 May, a duration of 201 days.

The wind frequency distribution indicates that the winds in the area are predominantly from approximately south and west and occur 12% and 10% of the time respectively. The average monthly wind speeds range between 13 km/hr (8 mph) and 16 km/hr (10 mph) while the maximum wind speeds range between 24 km/hr (15 mph) and 61 km/hr (38 mph). Maximum wind frequency distribution indicates that the maximum wind velocities are from the west to northwest and occur 45% of the time from those directions. A seasonal variation in wind speed and direction is evident with a higher frequency of winds from the west occurring in the winter than in the summer.

D.1.2 Atmospheric Stability

The dispersive qualities of the atmosphere are strongly influenced by the occurrence of different atmospheric stability conditions. Stability is strongly influenced by the thermal properties of the atmosphere or the temperature lapse rate. In a neutral atmosphere, the temperature decreases adiabatically with height, neither enhancing nor inhibiting dispersion. However, this condition is generally conducive to favourable dispersion because of mechanically induced turbulence. Under stable conditions, temperature increases with height (an inversion), winds are light and dispersion is inhibited. In an unstable atmosphere, the temperature decreases with height at a greater rate than at

neutral conditions and significant thermal turbulence exists; thus favourable dispersion conditions are created. Categories of stability conditions are based on stability classes developed by Pasquill (1961) and modified by Turner (1969), and are available in the form of STAR (STability ARray) data from AES (AES, 1983). Stability class distributions for Collins Bay were generated using the STAR program by MacLaren Engineers/Geocon (1984), (Table D.1.1). Data for 1972-87 were obtained for this project, but are not given herein.

TABLE D.1.1 ATMOSPHERIC STABILITY DISTRIBUTION (%)
 COLLINS BAY (1972-1980)

	Stability Class						Total
	A	B	C	D	E	F	
JAN	0	0	6.8	55.8	18.1	19.3	100
FEB	0	3.9	13.2	59.5	10.5	12.9	100
MAR	0	5.2	21.1	59.0	8.4	6.3	100
APR	0.4	11.6	22.7	59.7	3.1	2.5	100
MAY	0.5	13.5	27.0	56.3	1.4	1.3	100
JUN	0.7	16.6	28.3	51.2	1.7	1.5	100
JUL	0.3	14.6	29.4	52.4	2.1	1.2	100
AUG	0.6	11.2	2.7	61.8	1.8	1.9	100
SEP	0.1	4.7	15.9	70.4	4.9	4.0	100
OCT	0.0	1.1	7.9	80.3	6.6	4.1	100
NOV	0.0	0.2	4.4	75.1	10.5	9.7	100
DEC	0.0	0.0	4.9	62.9	15.3	16.9	100
Annual	0.2	6.9	17.0	62.0	7.1	6.8	100

(After MacLaren Engineers and Geocon, 1984)

The annual distributions show a very low frequency of unstable (A,B) conditions (7.1% of time); a high frequency of neutral (C,D) conditions (79% of time) and a relatively high frequency of stable (E,F) conditions (13.9% of time). The high frequency of stable atmosphere conditions gives rise to a high potential for ground-based inversions. An evaluation of the frequency of occurrence of these phenomena has shown them to be relatively frequent in Northern Canada (Munn et al., 1970). Early morning inversions occur on 50% to 70% of days. The frequency varies considerably by season as would be expected with more stable conditions in winter when solar effects on turbulence are at a minimum and wind speeds are low.

D.1.3 Mixing Height

The distance from ground level to the base of an elevated inversion is called the mixing height. This height is a measure of the depth through which pollutants are dispersed and diluted. The mixing height coupled with the mean wind passing through this height, provides a factor called the ventilation coefficient. The greater the ventilation coefficient, the greater the amount of diluting air passing through a region, thus lowering ambient contaminant concentration levels.

Mixing height, wind speed and ventilation coefficient data (Portelli, 1972) are summarized by season (Table D.1.2). Low ventilation coefficients ($6000 \text{ m}^2/\text{s}$) are an indication of a relatively low dilution potential for airborne contaminants.

TABLE D.1.2 MIXING HEIGHTS, WIND SPEEDS AND ESTIMATED VENTILATION COEFFICIENTS - McCLEAN LAKE AREA

	Mean Maximum Mixing Heights (m)	Mean Wind Speed Through The Mixing Layer (m/s, mph)	Mean Maximum Ventilation Coefficients (m^2/s)
Spring (Afternoon)	800	6.5 (14.5)	5200
Summer (Afternoon)	1300	6.5 (14.5)	8500
Autumn (Afternoon)	620	6.9 (15.4)	4300
Winter (Afternoon)	220	5.4 (12.1)	1200
Annual (Afternoon)	770	6.9 (15.4)	5300

(After MacLaren Engineers and Geocon, 1984)

The most serious potential for deterioration of the airshed is expected in the autumn and winter when a stagnant continental airmass lies over this area. During these seasons, strong ground-based inversions are expected, corresponding to poor dispersion qualities.

D.2 Assessment of Bioconcentration Factors

D.2.1 Calculation of BCF Values

All available measurements of radionuclides in water and in fish were compiled for the various lakes in Saskatchewan. These data are a subset of data compiled for all Canada (BEAK, 1987). Most of the larger database is from Saskatchewan, with limited representation from Ontario, British Columbia and the Northwest Territories. These data were used for the first time in this project for calculating BCF values.

Data on radionuclide concentrations in fish species are available from diverse sources, including government agencies, universities, mining companies, consulting firms, analytical laboratories, the published scientific literature and individual scientists. These data are contained in scientific journals, unpublished environmental impact assessments, government reports, conference proceedings, unpublished theses and monitoring reports from operating uranium mines. The radionuclide analyses of fish tissues have been made for a variety of reasons at different times and by different research groups. They have been analyzed and reported in a variety of ways and units. The sources of data are given in Section D2.2.

The associated "quality" of these data is variable from one study to another, and within a specific study (BEAK, 1987). Quality in this context refers to several factors, including:

- o the collection, handling and storage of the samples;
- o the analytical procedures followed;
- o the procedures of quality control and quality assurance followed; and
- o the occurrence of statistical anomalies (outliers) or values outside the normal range of values in the published Canadian and international literature.

The data have the following strengths and weaknesses:

- o Most of the radionuclide measurements are of U-total, Ra-226 and Pb-210 in fish. More data are needed for thorium, thorium isotopes and Po-210.

- o More detailed documentation of sampling and analytical methods, routine reporting of water and sediment determinations associated with fish samples, and routine sample exchange between laboratories as a means of assessing potential bias and comparability of different data sources are needed.
- o Documentation of sample storage times and conditions are seldom described, and detection limits and relative errors are seldom defined;
- o Most of the fish samples analyzed for uranium and thorium decay series radionuclides in Canada do **not** have corresponding water or sediment values which were determined from the same time period. Routine collection of ambient radionuclide content is required to estimate bioaccumulation, in cases where the lake water and sediment concentrations vary with time.
- o Analytical bias between laboratories is difficult to assess in the absence of fish tissue standards for uranium and thorium decay series radionuclides. Development of such standards would increase the confidence with which data from different studies can be compared. Until such time as these standards become available, interlaboratory exchange of samples during each study is the best method of assessing possible biases and incompatibilities between data sets.

Despite these difficulties, the data were used to estimate radionuclide bioconcentration factors for Rabbit Lake receiving waters (Hidden Bay, Wollaston Lake). The typical type of data available and the calculated bioconcentration factor (CF) are given in Table D2.1. The values of BCF are calculated as:

$$\text{BCF} = \frac{\text{flesh activity (Bq/kg wet weight flesh)}}{\text{water activity (Bq/L of water)}}$$

Values of BCF, which are starred, were based upon detection limit values for either the fish or for the water phase.

The data are variously reported on a wet weight basis for flesh, or whole fish; on an ash basis; or for component parts (bones, gonads, skin, liver). In Table D2.1, only flesh data reported on a wet weight or dry weight basis are used to estimate the concentration factors.

Inspection of Table D2.1 indicates that there are many values which include "less thans". Inspection of the database also indicates that there are very few fish samples for Wollaston Lake, particularly for whitefish and trout, the main diet of the potential receptors of concern in this study. Accordingly, for this assessment, all data from Saskatchewan have been grouped and analyzed to obtain bioconcentration factor estimates for all fish. As well, BCF values for whitefish and trout have been estimated from the Saskatchewan database.

Frequency histograms of the BCF's and log-normal probability plots are given respectively in Figures D2.1 and D2.2. The geometric mean of the BCF values for "data including less than" and for "data excluding less than" are summarized in Table D2.2. A linear regression line from the log-normal probability distribution plot is used to estimate the geometric mean. The regression line is indicated on each log-normal plot in Figure D2.2.

Analyses of the frequency histograms and log-normal plots indicate that the data generally fit a log-normal distribution. There are a few plots where this is questionable due to the paucity of data. But overall, it may be concluded that the data fit a log-normal distribution.

The BCF results indicate that there is not generally too much difference between BCF geometric mean values which include or exclude "less thans" for uranium, radium-226 and Pb-210, but there are differences for certain thorium and polonium data sets. For this study, the data excluding "less thans" are used to develop the estimates of geometric mean, geometric standard deviation and range given in Chapter 4.0 of the main body for the Bioconcentration Factors.

D2.2.2 Cluster Analysis of BCF Factors

Cluster analysis was carried out on the BCF data for uranium, radium-226 and Pb-210. Data for thorium was ignored due to its paucity. Three techniques were used: Baverage, Waverage and Wards. Results from Wards are used here because it searches for similarity in the variance structures, whereas the other two do not.

TABLE D2.1: TYPICAL TYPE OF DATA AVAILABLE FOR RADIONUCLIDE ACTIVITY IN FISH AND ASSOCIATED LAKE WATER

Source	Bay	Species	Weight Basis	Tissue	Radium-226			Lead-210			Uranium (T)			Th-230		
					Fish (pCi/kg)	Water (pCi/L)	CF (L/kg)	Fish (pCi/kg)	Water (pCi/L)	CF (L/kg)	Fish (ug/g)	Water (ug/L)	CF (L/kg)	Fish (pCi/g)	Water (pCi/L)	CF (L/kg)
Midwest EIA (BEAK, 1980)	Collins	Northern pike	wet	bone	100	0.5	200									
		Northern pike	wet	bone	100	0.5	200									
		Northern pike	wet	flesh	100	0.5	200*	-10	2	5*						
		Northern pike	wet	flesh	100	0.5	200*	-10	2	5*						
		Whitefish	wet	flesh	400	0.5	800	-10	2	5*						
EPS (ref. 5)	Hidden	Whitefish	ash	flesh	-100	-0.1	7.8*	-500	-0.5	7.8*	0.4	-0.06	52*	0.4	-0.3	10*
		Whitefish	ash	flesh	200	-0.1	16*	1,900	-0.5	30*	0.8	-0.06	104*	-0.3	-0.3	7.8*
		Whitefish	ash	flesh	-100	-0.1	7.8*	-500	-0.5	7.8*	0.3	-0.06	39*	-0.3	-0.3	7.8*
		Sucker	ash	flesh	-100	-0.1	10*	1,200	-0.5	24*	0.4	-0.06	67*	-0.3	-0.3	10*
		Longnose sucker	ash	flesh	300	-0.1	60*	600	-0.5	24*	0.4	-0.06	130*	-0.3	-0.3	20*
		Longnose sucker	ash	flesh	300	-0.1	60*	800	-0.5	32*	0.6	-0.06	200*	-0.3	-0.3	20*
		Longnose sucker	ash	flesh	300	-0.1	60*	-500	-0.5	20*	0.7	-0.06	230*	-0.3	-0.3	20*
		Longnose sucker	ash	flesh	200	-0.1	40*	-500	-0.5	20*	0.7	-0.06	230*	-0.3	-0.3	20*
		Longnose sucker	ash	flesh	200	-0.1	40*	1,400	-0.5	56*	1.0	-0.06	17*	-0.3	-0.3	20*
Gulf Minerals EIA (ref. 31)	Collins	Whitefish	ash	flesh	110	0.0017	500	700	0.0176	310						
		Whitefish	ash	bone	120	0.0017	13,000	400	0.0176	4,320						
		Northern pike ¹	ash	flesh	70	0.0017	410	5,900	0.0176	3,350						
		Northern pike ²	ash	bone	80	0.0017	9,400	800	0.0176	9,090						
		Longnose sucker	ash	flesh	50	0.0017	590	500	0.0176	568						
		Longnose sucker	ash	bone	140	0.0017	21,000	2,800	0.0176	41,400						

* Either water concentration or fish concentration of radionuclide below detection.

¹ Used 1% ash:FW ratio.² Used 20% ash:FW ratio.

For all other weight conversions, mean ash contents were taken from Swanson (1983).

TABLE D2.1: TYPICAL TYPE OF DATA AVAILABLE FOR RADIONUCLIDE ACTIVITY IN FISH AND ASSOCIATED LAKE WATER

Source	Bay	Species	Weight Basis	Tissue	Radium-226			Lead-210			Uranium		
					Fish (Bq/g)	Water (Bq/L)	CF (L/kg)	Fish (Bq/g)	Water (Bq/L)	CF (L/kg)	Fish (ug/g)	Water (ug/L)	CF (L/kg)
Eldorado (ref. 29, 30)	Hidden	Lake trout	wet	flesh	0.00007	0.009	7.8	-0.0007	-	-	-0.04	2.5	16.0*
	Hidden	Lake trout	wet	bone	-0.0007	0.009	78*	0.01	-	-	-0.4	2.5	160.0*
Data from Monitoring Reports, 1980-84	POW	Lake trout	wet	flesh	-0.00007	0.008	8.8	-0.0007	0.42	1.7*	-0.04	17.8	2.3*
	POW	Lake trout	wet	bone	-0.00007	0.008	88*	0.03	0.42	71.4	-0.4	17.8	22.5*
Data from Monitoring Reports, 1980-84	POW	Lake trout	wet	flesh	0.00003	0.008	3.8	0.006	0.42	14.3	0.004	17.8	0.2
	POW	Lake trout	wet	bone	-0.0006	0.008	75*	0.007	0.42	16.7	0.01	17.8	0.6
Data from Monitoring Reports, 1980-84	POW	Lake trout	wet	flesh	0.00003	0.008	3.8	0.002	0.42	4.8	0.038	17.8	2.1
	POW	Lake trout	wet	bone	0.0006	0.008	75	0.004	0.42	9.5	0.01	17.8	0.6
Data from Monitoring Reports, 1980-84	POW	Lake trout	wet	flesh	-0.005	0.06	83*	-0.005	0.37	13.5*	-0.01	7.0	1.4*
	POW	Lake trout	wet	bone	-0.005	0.06	83*	-0.008	0.37	21.6*	-0.01	7.0	1.4*
Data from Monitoring Reports, 1980-84	Collins	Northern pike	wet	flesh	-0.00006	-	-	-0.0007	-	-	-0.1	-	-
	Collins	Northern pike	wet	bone	-0.0004	-	-	0.006	-	-	-0.3	-	-
Data from Monitoring Reports, 1980-84	Hidden	Northern pike	wet	flesh	-0.00007	0.009	7.8*	0.002	-	-	-0.04	2.5	16.0*
	Hidden	Northern pike	wet	bone	-0.0009	0.009	100*	0.007	-	-	-0.4	2.5	160.0*
Data from Monitoring Reports, 1980-84	POW	Northern pike	wet	flesh	-0.00007	0.008	8.8*	0.006	0.42	14.3	-0.04	17.8	2.2*
	POW	Northern pike	wet	bone	-0.0007	0.008	88*	0.02	0.42	47.6	-0.4	17.8	22.5*
Data from Monitoring Reports, 1980-84	Hidden	Northern pike	wet	flesh	0.0004	0.009	16	-0.004	-	-	0.004	2.5	1.6
	Hidden	Northern pike	wet	bone	0.002	0.009	220	-0.007	-	-	0.3	2.5	120
Data from Monitoring Reports, 1980-84	POW	Northern pike	wet	flesh	0.0008	0.008	13	-0.006	0.42	14.3*	0.004	17.8	0.2
	POW	Northern pike	wet	bone	-0.0001	0.008	13*	0.04	0.42	95.2	0.05	17.8	2.8
Data from Monitoring Reports, 1980-84	Hidden	Northern pike	wet	flesh	0.0002	0.009	22	-0.002	-	-	0.008	2.5	3.2
	Hidden	Northern pike	wet	bone	-0.0005	0.009	56*	0.002	-	-	0.06	2.5	24.0
Data from Monitoring Reports, 1980-84	POW	Northern pike	wet	flesh	0.0002	0.008	25	-0.002	0.42	4.8*	0.018	17.8	1.0
	POW	Northern pike	wet	bone	0.0025	0.008	310	0.017	0.42	40.5	0.03	17.8	1.7
Data from Monitoring Reports, 1980-84	Collins	Northern pike	wet	flesh	-0.005	-	-	-0.005	-	-	-0.01	-	-
	Collins	Northern pike	wet	bone	-0.005	-	-	0.005	-	-	0.02	-	-
Data from Monitoring Reports, 1980-84	Hidden	Northern pike	wet	flesh	-0.005	0.009	560*	-0.005	-	-	0.062	2.5	24.8
	Hidden	Northern pike	wet	bone	-0.005	0.009	560*	0.005	-	-	-0.01	2.5	4.0*
Data from Monitoring Reports, 1980-84	POW	Northern pike	wet	flesh	-0.005	0.06	83*	-0.005	0.37	13.5*	-0.01	7.0	1.4*
	POW	Northern pike	wet	bone	-0.005	0.06	83*	-0.005	0.37	13.5*	0.037	7.0	5.3*

TABLE D2.2: GEOMETRIC MEAN OF BIOCONCENTRATION FACTORS OF URANIUM DECAY SERIES RADIONUCLIDES IN SASKATCHEWAN LAKE

Nuclide	Fish	Including LT	Excluding LT
Uranium	All fish	1.3	1.3
	Whitefish	0.63	6.4
	Trout	-	8.8
Th-230	All fish	6.9	1.2
	Whitefish	1.7	1.7
	Trout	-	-
Ra-226	All fish	9.4	9.5
	Whitefish	6.6	7.1
	Trout	-	6.0
Pb-210	All fish	9.5	13.5
	Whitefish	12.3	16.7
	Trout	-	-
Po-210	All fish	-	8.5
	Whitefish	-	10.0
	Trout	-	13.8

Figure D2.1a

Page 22 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGUT

Count	Midpoint
0	-2.2 I
0	-2.1 I
2	-2.0 IXXXXX
0	-1.9 I
0	-1.8 I
2	-1.7 IXXXXX
0	-1.6 I
1	-1.5 IXX
2	-1.4 IXXXXX
1	-1.3 IXX
6	-1.2 IXXXXXXXXXXXXXX
1	-1.1 IXX
13	-1.0 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
20	-.9 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
13	-.8 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
10	-.7 IXXXXXXXXXXXXXXXXXXXX
7	-.6 IXXXXXXXXXXXX
3	-.5 IXXXXXX
2	-.4 IXXXXX
3	-.3 IXXXXXX
2	-.2 IXXXXX
7	-.1 IXXXXXXXXXXXX
4	.0 IXXXXXXXXXX
6	.1 IXXXXXXXXXXXX
14	.2 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
11	.3 IXXXXXXXXXXXXXXXXXXXX
8	.4 IXXXXXXXXXXXX
16	.5 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
15	.6 IXXXXXXXXXXXXXXXXXXXX
10	.7 IXXXXXXXXXXXX
9	.8 IXXXXXXXXXXXX
8	.9 IXXXXXXXXXXXX
6	1.0 IXXXXXXXXXX
3	1.1 IXXXXXX
9	1.2 IXXXXXXXXXXXX
0	1.3 I
2	1.4 IXXXXX
4	1.5 IXXXXXXXXXX
4	1.6 IXXXXXXXXXX
3	1.7 IXXXXXX
3	1.8 IXXXXXX
0	1.9 I
1	2.0 IXX
1	2.1 IXX
2	2.2 IXXXXX
1	2.3 IXX
0	2.4 I
0	2.5 I
1	2.6 IXX
0	2.7 I
0	2.8 I

I.....+.....I.....+.....I.....+.....I.....+.....I.....+.....I

0 4 8 12 16 20

Histogram Frequency

Page 23 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGUT

Mean	.124	Std Err	.060	Median	.243
Mode	-.921	Std Dev	.919	Variance	.844
Kurtosis	-.610	S E Kurt	.316	Skewness	.108
S E Skew	.158	Range	4.557	Minimum	-2.000
Maximum	2.557	Sum	29.221		

Valid Cases 236 Missing Cases 0

Figure D2.1b-----

Page 11 FREQUENCY HISTOGRAM FOR WHITEFISH

LGUT

Count	Midpoint
1	-1.975 IXX
0	-1.900 I
0	-1.825 I
0	-1.750 I
0	-1.675 I
0	-1.600 I
1	-1.525 IXX
0	-1.450 I
2	-1.375 IXXXXX
1	-1.300 IXX
4	-1.225 IXXXXXXXXXX
2	-1.150 IXXXXX
4	-1.075 IXXXXXXXXXX
5	-1.000 IXXXXXXXXXX
12	-.925 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
17	-.850 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
8	-.775 IXXXXXXXXXXXXXXXXXXXX
8	-.700 IXXXXXXXXXXXXXXXXXXXX
5	-.625 IXXXXXXXXXXXX
2	-.550 IXXXXX
1	-.475 IXX
0	-.400 I
1	-.325 IXX
0	-.250 I
1	-.175 IXX
1	-.100 IXX
4	-.025 IXXXXXXXXXX
3	.050 IXXXXXX
4	.125 IXXXXXXXXXX
3	.200 IXXXXXX
2	.275 IXXXXX
5	.350 IXXXXXXXXXXXX
3	.425 IXXXXXX
3	.500 IXXXXXX
3	.575 IXXXXXX
1	.650 IXX
2	.725 IXXXXX
3	.800 IXXXXXX
4	.875 IXXXXXXXXXX
3	.950 IXXXXXX
0	1.025 I
1	1.100 IXX
3	1.175 IXXXXXX
1	1.250 IXX
0	1.325 I
0	1.400 I
0	1.475 I
2	1.550 IXXXXX
1	1.625 IXX
0	1.700 I
1	1.775 IXX

I.....+.....I.....+.....I.....+.....I.....+.....I.....+.....I

0 4 8 12 16 20

Histogram Frequency

Page 12 FREQUENCY HISTOGRAM FOR WHITEFISH

LGUT

Mean	-.278	Std Err	.072	Median	-.678
Mode	-.921	Std Dev	.819	Variance	.670
Kurtosis	-.694	S E Kurt	.425	Skewness	.590
S E Skew	.214	Range	3.787	Minimum	-2.000
Maximum	1.787	Sum	-35.570		

Valid Cases 128 Missing Cases 0

Figure D2.1c

Page 4 FREQUENCY HISTOGRAM FOR TROUT.

LGUT

Count	Midpoint
0	-.925 I
0	-.850 I
0	-.775 I
0	-.700 I
0	-.625 I
0	-.550 I
0	-.475 I
0	-.400 I
1	-.325 IXXXXXXXXXX
0	-.250 I
0	-.175 I
0	-.100 I
1	-.025 IXXXXXXXXXX
0	.050 I
2	.125 IXXXXXXXXXXXXXXXXXXXX
1	.200 IXXXXXXXXXX
0	.275 I
1	.350 IXXXXXXXXXX
0	.425 I
0	.500 I
0	.575 I
0	.650 I
0	.725 I
0	.800 I
0	.875 I
0	.950 I
0	1.025 I
0	1.100 I
0	1.175 I
0	1.250 I
0	1.325 I
0	1.400 I
0	1.475 I
1	1.550 IXXXXXXXXXX
0	1.625 I
0	1.700 I
0	1.775 I
1	1.850 IXXXXXXXXXX
0	1.925 I
0	2.000 I
0	2.075 I
0	2.150 I
2	2.225 IXXXXXXXXXXXXXXXXXXXX
1	2.300 IXXXXXXXXXX
0	2.375 I
0	2.450 I
0	2.525 I
0	2.600 I
0	2.675 I
0	2.750 I
0	2.825 I
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Histogram Frequency	

Page 5 FREQUENCY HISTOGRAM FOR TROUT.

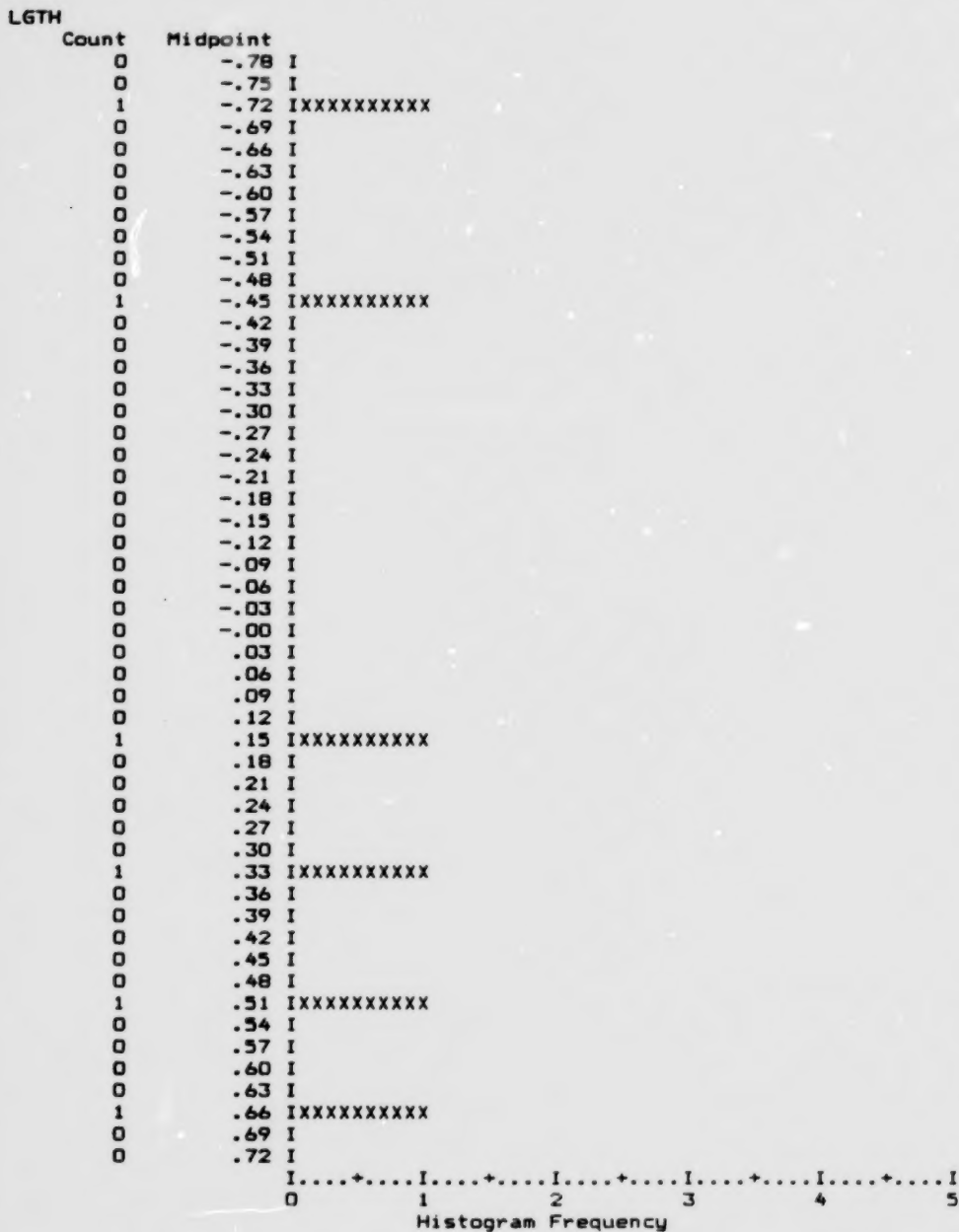
LGUT

Mean	.946	Std Err	.318	Median	.334
Mode	.093	Std Dev	1.056	Variance	1.115
Kurtosis	-2.055	S E Kurt	1.279	Skewness	.241
S E Skew	.661	Range	2.622	Minimum	-.357
Maximum	2.266	Sum	10.401		

Valid Cases 11 Missing Cases 3

Figure D2.1d

Page 26 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.



Page 27 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGTH

Mean	.078	Std Err	.225	Median	.237
Mode	-.721	Std Dev	.551	Variance	.304
Kurtosis	-1.348	S E Kurt	1.741	Skewness	-.656
S E Skew	.845	Range	1.387	Minimum	-.721
Maximum	.666	Sum	.470		

Valid Cases 6 Missing Cases 230

Figure D2.1e

Page 15 FREQUENCY HISTOGRAM FOR WHITEFISH

LGTH

Count	Midpoint
0	-.520 I
0	-.495 I
0	-.470 I
1	-.445 IXXXXXXXXXX
0	-.420 I
0	-.395 I
0	-.370 I
0	-.345 I
0	-.320 I
0	-.295 I
0	-.270 I
0	-.245 I
0	-.220 I
0	-.195 I
0	-.170 I
0	-.145 I
0	-.120 I
0	-.095 I
0	-.070 I
0	-.045 I
0	-.020 I
0	.005 I
0	.030 I
0	.055 I
0	.080 I
0	.105 I
0	.130 I
1	.155 IXXXXXXXXXX
0	.180 I
0	.205 I
0	.230 I
0	.255 I
0	.280 I
0	.305 I
1	.330 IXXXXXXXXXX
0	.355 I
0	.380 I
0	.405 I
0	.430 I
0	.455 I
0	.480 I
1	.505 IXXXXXXXXXX
0	.530 I
0	.555 I
0	.580 I
0	.605 I
0	.630 I
1	.655 IXXXXXXXXXX
0	.680 I
0	.705 I
0	.730 I

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Histogram Frequency

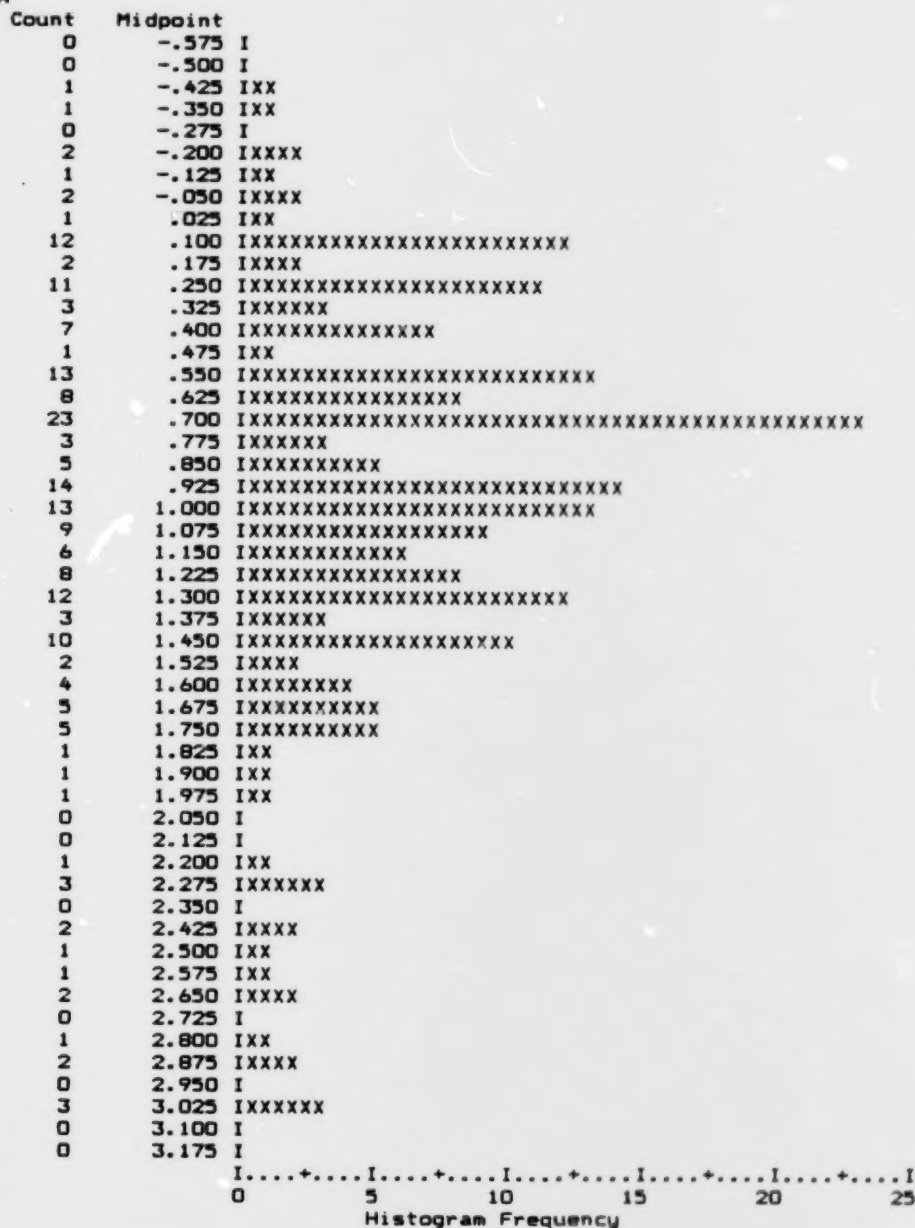
Page 16 FREQUENCY HISTOGRAM FOR WHITEFISH

LGTH

Mean	.238	Std Err	.194	Median	.324
Mode	-.456	Std Dev	.434	Variance	.188
Kurtosis	1.568	S E Kurt	2.000	Skewness	-1.209
S E Skew	.913	Range	1.122	Minimum	-.456
Maximum	.666	Sum	1.191		

Valid Cases 5 Missing Cases 123

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LGRA

Page 21 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGRA

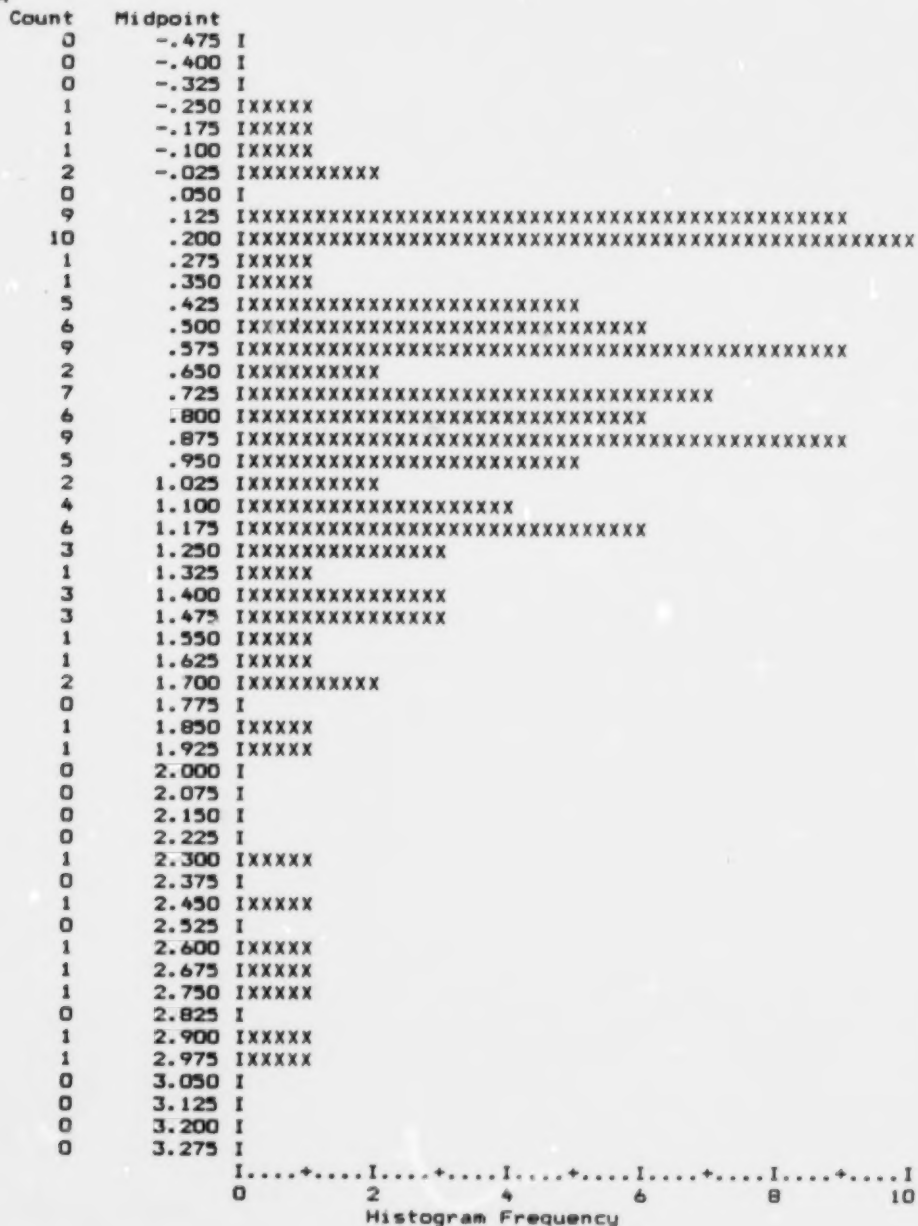
Mean	.978	Std Err	.048	Median	.892
Mode	.699	Std Dev	.685	Variance	.470
Kurtosis	.878	S E Kurt	.337	Skewness	.846
S E Skew	.169	Range	3.478	Minimum	-.444
Maximum	3.034	Sum	201.541		

Valid Cases	206	Missing Cases	30
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Figure D2.1g

Page 9 FREQUENCY HISTOGRAM FOR WHITEFISH

LGRA



Page 10 FREQUENCY HISTOGRAM FOR WHITEFISH

LGRA

Mean	.850	Std Err	.064	Median	.749
Mode	.223	Std Dev	.667	Variance	.445
Kurtosis	1.747	S E Kurt	.457	Skewness	1.212
S E Skew	.230	Range	3.235	Minimum	-.237
Maximum	2.998	Sum	93.467		

Valid Cases 110 Missing Cases 18

Page 2 FREQUENCY HISTOGRAM FOR TROUT.

Page 3 FREQUENCY HISTOGRAM FOR TROUT.

Valid Cases	14	Missing Cases	0
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Figure D2-14

Page 24 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGP8

Count	Midpoint
1	-.12 IXX
0	-.07 I
0	-.02 I
0	.03 I
0	.08 I
2	.13 IXXXXX
2	.18 IXXXXX
1	.23 IXX
2	.28 IXXXXX
3	.33 IXXXXXXXX
1	.38 IXX
0	.43 I
2	.48 IXXXXX
2	.53 IXXXXX
3	.58 IXXXXXXXX
0	.63 I
4	.68 IXXXXXXXXXX
2	.73 IXXXXX
2	.78 IXXXXX
7	.83 IXXXXXXXXXXXXXXXXXX
17	.88 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
4	.93 IXXXXXXXXXX
11	.98 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
9	1.03 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5	1.08 IXXXXXXXXXXXX
10	1.13 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
9	1.18 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6	1.23 IXXXXXXXXXXXX
10	1.28 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
2	1.33 IXXXXX
3	1.38 IXXXXXXXX
3	1.43 IXXXXXXXX
4	1.48 IXXXXXXXXXX
5	1.53 IXXXXXXXXXXXX
3	1.58 IXXXXXX
4	1.63 IXXXXXXXXXX
4	1.68 IXXXXXXXXXX
2	1.73 IXXXXX
1	1.78 IXX
2	1.83 IXXXXX
3	1.88 IXXXXXXXX
0	1.93 I
3	1.98 IXXXXXX
1	2.03 IXX
2	2.08 IXXXXX
1	2.13 IXX
1	2.18 IXX
0	2.23 I
1	2.28 IXX
0	2.33 I
1	2.38 IXX

I.....+.....I.....+.....I.....+.....I.....+.....I.....+.....I.....+

0 4 8 12 16 20

Histogram Frequency

Page 25 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

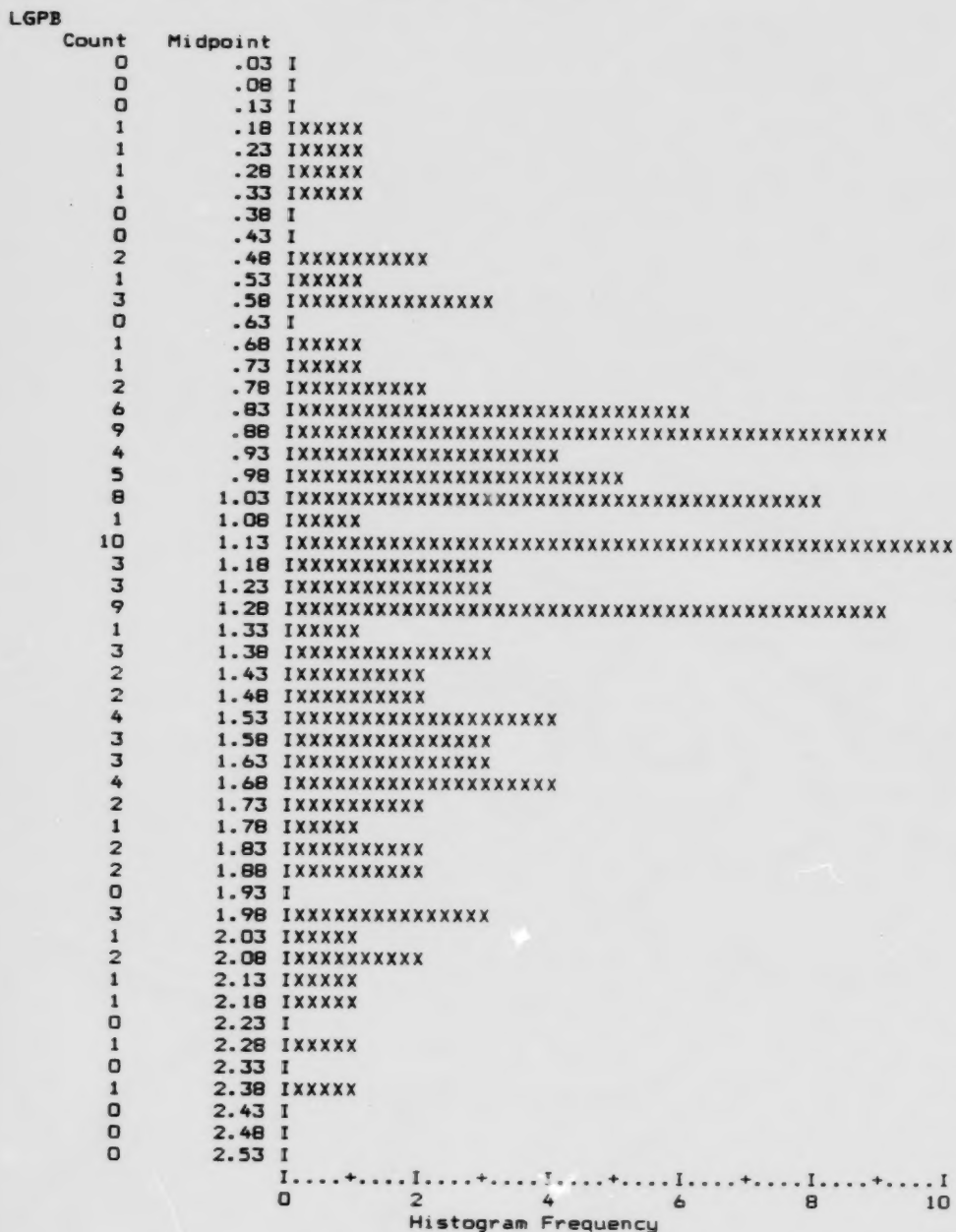
LGPB

Mean	1.134	Std Err	.037	Median	1.114
Mode	1.000	Std Dev	.466	Variance	.217
Kurtosis	.207	S E Kurt	.380	Skewness	.117
S E Skew	.191	Range	2.529	Minimum	-.131
Maximum	2.398	Sum	182.647		

Valid Cases	161	Missing Cases	75
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Figure D2.1j

Page 13 FREQUENCY HISTOGRAM FOR WHITEFISH



Page 14 FREQUENCY HISTOGRAM FOR WHITEFISH

LGPB

Mean	1.222	Std Err	.044	Median	1.133
Mode	.892	Std Dev	.461	Variance	.213
Kurtosis	-.172	S E Kurt	.455	Skewness	.256
S E Skew	.229	Range	2.243	Minimum	.155
Maximum	2.398	Sum	135.617		

Valid Cases 111 Missing Cases 17

Figure D2.1k

Page 28 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGPO

Count	Midpoint
0	-.04 I
0	.01 I
0	.06 I
2	.11 IXXXXXXXXXXXXXXXXXXXXX
0	.16 I
3	.21 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0	.26 I
0	.31 I
0	.36 I
0	.41 I
0	.46 I
0	.51 I
0	.56 I
0	.61 I
0	.66 I
0	.71 I
3	.76 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0	.81 I
0	.86 I
0	.91 I
0	.96 I
1	1.01 IXXXXXXXXXX
2	1.06 IXXXXXXXXXXXXXXXXXXXXX
0	1.11 I
0	1.16 I
1	1.21 IXXXXXXXXXX
0	1.26 I
2	1.31 IXXXXXXXXXXXXXXXXXXXXX
0	1.36 I
0	1.41 I
0	1.46 I
0	1.51 I
0	1.56 I
1	1.61 IXXXXXXXXXX
0	1.66 I
0	1.71 I
0	1.76 I
1	1.81 IXXXXXXXXXX
0	1.86 I
0	1.91 I
0	1.96 I
0	2.01 I
0	2.06 I
0	2.11 I
0	2.16 I
0	2.21 I
0	2.26 I
1	2.31 IXXXXXXXXXX
0	2.36 I
0	2.41 I
0	2.46 I
I.....+.....I.....+.....I.....+.....I.....+.....I.....+.....I	
0	1 2 3 4 5
Histogram Frequency	

Page 29 FREQUENCY HISTOGRAM FOR SASKATCHEWAN.

LGPO

Mean	.931	Std Err	.154	Median	1.000
Mode	.223	Std Dev	.634	Variance	.401
Kurtosis	-.277	S E Kurt	1.063	Skewness	.416
S E Skew	.550	Range	2.183	Minimum	.114
Maximum	2.297	Sum	15.820		

Valid Cases 17 Missing Cases 219

Figure D2.11

Page 17 FREQUENCY HISTOGRAM FOR WHITEFISH

LGPO

Count	Midpoint	
0	-.04	I
0	.00	I
0	.04	I
0	.08	I
2	.12	XXXXXXXXXXXXXXXXXXXX
0	.16	I
0	.20	I
0	.24	I
0	.28	I
0	.32	I
0	.36	I
0	.40	I
0	.44	I
0	.48	I
0	.52	I
0	.56	I
0	.60	I
0	.64	I
0	.68	I
0	.72	I
0	.76	I
0	.80	I
0	.84	I
0	.88	I
0	.92	I
0	.96	I
0	1.00	I
0	1.04	I
1	1.08	XXXXXXXXXX
0	1.12	I
0	1.16	I
0	1.20	I
0	1.24	I
1	1.28	XXXXXXXXXX
0	1.32	I
0	1.36	I
0	1.40	I
0	1.44	I
0	1.48	I
0	1.52	I
0	1.56	I
1	1.60	XXXXXXXXXX
0	1.64	I
0	1.68	I
0	1.72	I
0	1.76	I
1	1.80	XXXXXXXXXX
0	1.84	I
0	1.88	I
0	1.92	I
0	1.96	I
		I.....I.....I.....I.....I.....I
		0 1 2 3 4 5
		Histogram Frequency

Page 18 FREQUENCY HISTOGRAM FOR WHITEFISH

LGPO

Mean	.998	Std Err	.298	Median	1.179
Mode	.114	Std Dev	.731	Variance	.534
Kurtosis	-1.842	S E Kurt	1.741	Skewness	-.469
S E Skew	.845	Range	1.699	Minimum	.114
Maximum	1.813	Sum	5.990		

Valid Cases 6 Missing Cases 122

Figure D2.lm

Page 6 FRREQUENCY HISTOGRAM FOR TROUT.

LGPO

Count	Midpoint	
0	.6942	I
0	.7275	I
3	.7608	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
0	.7941	I
0	.8274	I
0	.8607	I
0	.8940	I
0	.9273	I
0	.9606	I
0	.9939	I
0	1.0272	I
1	1.0605	XXXXXXXXXX
0	1.0938	I
0	1.1271	I
0	1.1604	I
0	1.1937	I
1	1.2270	XXXXXXXXXX
0	1.2603	I
0	1.2936	I
0	1.3269	I
0	1.3602	I
0	1.3935	I
0	1.4268	I
0	1.4601	I
0	1.4934	I
0	1.5267	I
0	1.5600	I
0	1.5933	I
0	1.6266	I
0	1.6599	I
0	1.6932	I
0	1.7265	I
0	1.7598	I
0	1.7931	I
0	1.8264	I
0	1.8597	I
0	1.8930	I
0	1.9263	I
0	1.9596	I
0	1.9929	I
0	2.0262	I
0	2.0595	I
0	2.0928	I
0	2.1261	I
0	2.1594	I
0	2.1927	I
0	2.2260	I
0	2.2593	I
1	2.2926	XXXXXXXXXX
0	2.3259	I
0	2.3592	I

I.....I.....I.....I.....I.....I.....I.....I.....I
 0 1 2 3 4 5
 Histogram Frequency

Page 7 FREQUENCY HISTOGRAM FOR TROUT.

LGPO

Mean	1.140	Std Err	.245	Median	.904
Mode	.754	Std Dev	.601	Variance	.361
Kurtosis	3.756	S E Kurt	1.741	Skewness	1.905
S E Skew	.845	Range	1.544	Minimum	.754
Maximum	2.297	Sum	6.843		

Valid Cases 6 Missing Cases 8

Page 2 FREQUENCY HISTOGRAMS FOR WHITEFISH INCLUDES LT'S

Count	Midpoint
0	-.575 I
0	-.500 I
0	-.425 I
2	-.350 IXXXXX
0	-.275 I
8	-.200 IXXXXXXXXXXXXXXXXXXXXXX
1	-.125 IXX
2	-.050 IXXXXX
0	.025 I
10	.100 IXXXXXXXXXXXXXXXXXXXXXXXXXX
0	.175 I
15	.250 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
13	.325 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5	.400 IXXXXXXXXXXXX
1	.475 IXX
9	.550 IXXXXXXXXXXXXXXXXXXXXXXX
11	.625 IXXXXXXXXXXXXXXXXXXXXXXX
16	.700 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6	.775 IXXXXXXXXXXXX
4	.850 IXXXXXXXXXX
18	.925 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
1	1.000 IXX
10	1.075 IXXXXXXXXXXXXXXXXXXXXXXX
3	1.150 IXXXXXXX
8	1.225 IXXXXXXXXXXXXXXXXXXXX
1	1.300 IXX
4	1.375 IXXXXXXXXXX
4	1.450 IXXXXXXXXXX
3	1.525 XXXXXXXX
1	1.600 IXX
1	1.675 IXX
2	1.750 IXXXXX
3	1.825 IXXXXXXX
1	1.900 IXX
1	1.975 IXX
0	2.050 I
4	2.125 IXXXXXXXXXX
0	2.200 I
3	2.275 IXXXXXXX
0	2.350 I
0	2.425 I
1	2.500 IXX
0	2.575 I
2	2.650 IXXXXX
0	2.725 I
1	2.800 IXX
1	2.875 IXX
0	2.950 I
1	3.025 IXX
0	3.100 I
0	3.175 I

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0 4 8 12 16 20

Histogram Frequency

Page 3 FREQUENCY HISTOGRAMS FOR WHITEFISH INCLUDES LT'S

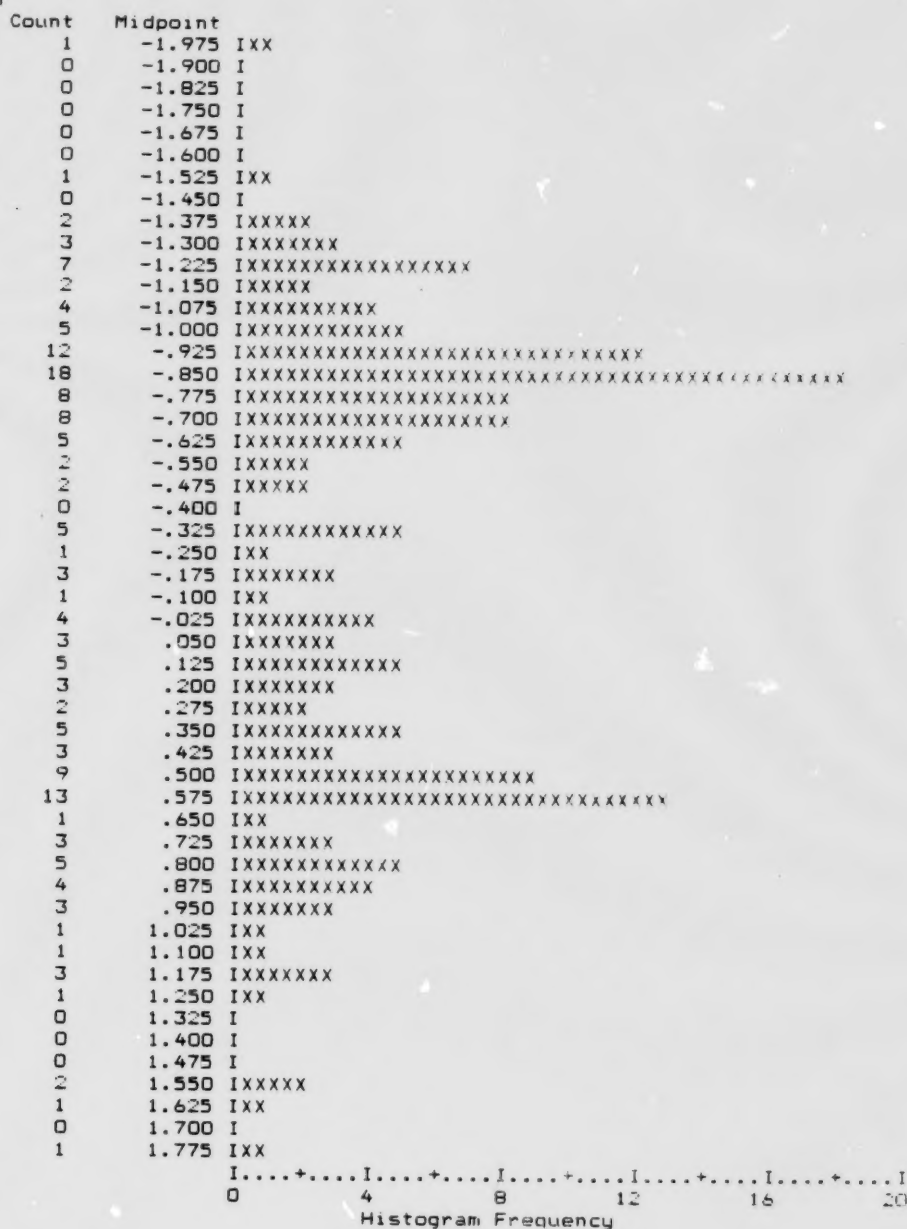
Mean	.817	Std Err	.051	Median	.699
Mode	.223	Std Dev	.675	Variance	.456
Kurtosis	.941	S E Kurt	.363	Skewness	.954
S E Skew	.183	Range	3.365	Minimum	-.367
Maximum	2.998	Sum	144.687		

Valid Cases	177	Missing Cases	0
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Figure D2.1o

Page 4 FREQUENCY HISTOGRAMS FOR WHITEFISH INCLUDES LT'S

LGUT



Page 5 FREQUENCY HISTOGRAMS FOR WHITEFISH INCLUDES LT'S

LGUT

Mean	-.203	Std Err	.063	Median	-.319
Mode	.569	Std Dev	.806	Variance	.650
Kurtosis	-.984	S E Kurt	.378	Skewness	.316
S E Skew	.190	Range	3.787	Minimum	-2.000
Maximum	1.787	Sum	-33.045		

Valid Cases 163 Missing Cases 14

Figure D2.1p

Page 7 FREQUENCY HISTOGRAMS FOR SASKATCHEWAN INCLUDES LT'S

LGRA	Count	Midpoint
	0	-.575 I
	0	-.500 I
	1	-.425 IX
	3	-.350 IXX
	1	-.275 IX
	9	-.200 IXXXXXX
	1	-.125 IX
	2	-.050 IX
	1	.025 IX
	13	.100 IXXXXXXXXXX
	2	.175 IX
	17	.250 IXXXXXXXXXXXX
	15	.325 IXXXXXXXXXXXX
	9	.400 IXXXXXX
	1	.475 IX
	16	.550 IXXXXXXXXXXXX
	13	.625 IXXXXXXXXXX
	65	.700 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
	8	.775 IXXXXXX
	5	.850 IXXX
	18	.925 IXXXXXXXXXXXX
	34	1.000 IXXXXXXXXXXXXXXXXXXXXXXXXXXXX
	15	1.075 IXXXXXXXXXX
	6	1.150 IXXXX
	9	1.225 IXXXXXX
	14	1.300 IXXXXXXXXXX
	6	1.375 IXXXX
	13	1.450 IXXXXXXXXXX
	9	1.525 IXXXXXX
	7	1.600 IXXXXXX
	5	1.675 IXXX
	7	1.750 IXXXXXX
	4	1.825 IXXX
	1	1.900 IX
	4	1.975 IXXX
	1	2.050 IX
	7	2.125 IXXXXX
	2	2.200 IX
	9	2.275 IXXXXXX
	0	2.350 I
	4	2.425 IXXX
	1	2.500 IX
	1	2.575 IX
	4	2.650 IXXX
	0	2.725 I
	1	2.800 IX
	2	2.875 IX
	0	2.950 I
	3	3.025 IXX
	0	3.100 I
	0	3.175 I
		I.....+.....I.....+.....I.....+.....I.....+.....I.....+.....I
		0 15 30 45 60 75
		Histogram Frequency

Page 8 FREQUENCY HISTOGRAMS FOR SASKATCHEWAN INCLUDES LT'S

LGRA

Mean	.974	Std Err	.035	Median	.892
Mode	.699	Std Dev	.678	Variance	.459
Kurtosis	.449	S E Kurt	.253	Skewness	.715
S E Skew	.127	Range	3.478	Minimum	-.444
Maximum	3.034	Sum	359.409		

Valid Cases 369 Missing Cases 0

Figure D2.1q

Page 9 FREQUENCY HISTOGRAMS FOR SASKATCHEWAN INCLUDES LT'S

LGUT

Count	Midpoint
0	-2.2 I
0	-2.1 I
2	-2.0 IXX
0	-1.9 I
0	-1.8 I
2	-1.7 IXX
0	-1.6 I
1	-1.5 IX
6	-1.4 IXXXXXXX
3	-1.3 IXXXX
9	-1.2 IXXXXXXXXXXXX
1	-1.1 IX
13	-1.0 IXXXXXXXXXXXXXXXXX
20	-.9 IXXXXXXXXXXXXXXXXXXXXX
17	-.8 IXXXXXXXXXXXXXXXXXXXXX
11	-.7 IXXXXXXXXXXXXXXXXX
10	-.6 IXXXXXXXXXXXXX
4	-.5 IXXXXX
3	-.4 IXXXX
8	-.3 IXXXXXXXXXX
10	-.2 IXXXXXXXXXXXXX
12	-.1 IXXXXXXXXXXXXXXXXX
8	.0 IXXXXXXXXXX
8	.1 IXXXXXXXXXX
28	.2 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
11	.3 IXXXXXXXXXXXXX
9	.4 IXXXXXXXXXX
23	.5 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
31	.6 IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
12	.7 IXXXXXXXXXXXXX
12	.8 IXXXXXXXXXXXXX
9	.9 IXXXXXXXXXX
9	1.0 IXXXXXXXXXX
6	1.1 IXXXXXX
9	1.2 IXXXXXXXXXX
1	1.3 IX
2	1.4 IXX
7	1.5 IXXXXXXXXXX
4	1.6 IXXXXX
3	1.7 IXXXX
3	1.8 IXXXX
0	1.9 I
1	2.0 IX
1	2.1 IX
2	2.2 IXX
1	2.3 IX
0	2.4 I
0	2.5 I
1	2.6 IX
0	2.7 I
0	2.8 I

I.....I.....I.....I.....I.....I.....I.....I.....I.....I

0 8 16 24 32 40

Histogram Frequency

Page 10 FREQUENCY HISTOGRAMS FOR SASKATCHEWAN INCLUDES LT'S

LGUT

Mean	.120	Std Err	.047	Median	.223
Mode	.223	Std Dev	.859	Variance	.738
Kurtosis	-.439	S E Kurt	.266	Skewness	.030
S E Skew	.134	Range	4.557	Minimum	-2.000
Maximum	2.557	Sum	39.930		

Valid Cases	333	Missing Cases	36
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Figure D2.2 a

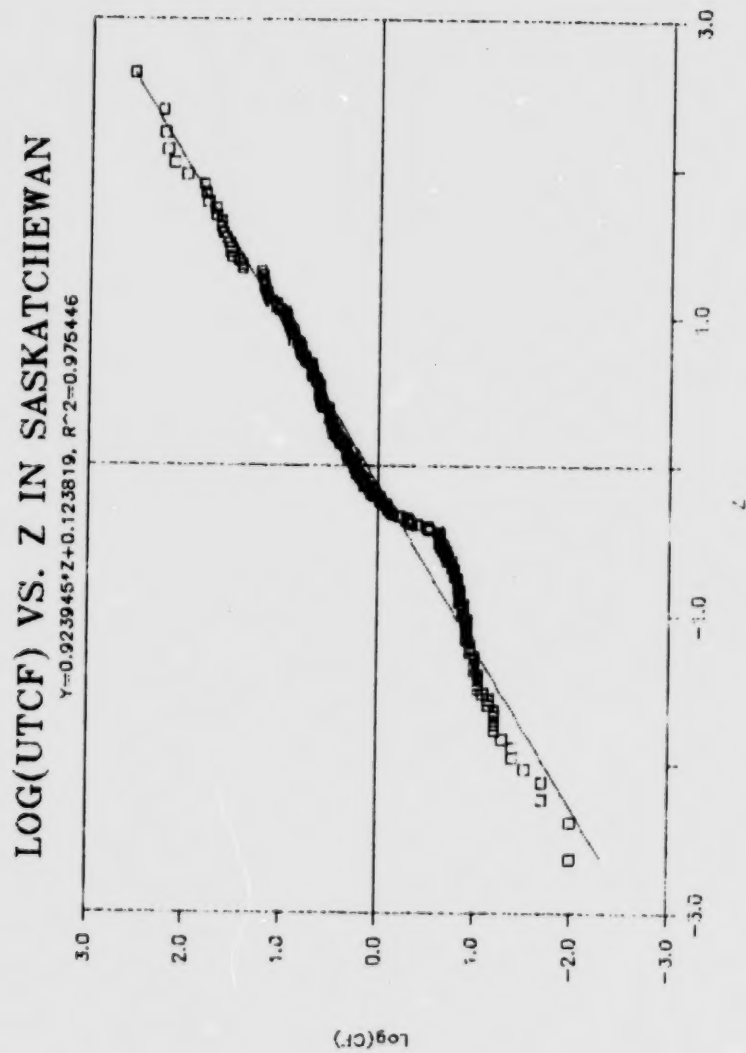


Figure D2.2b

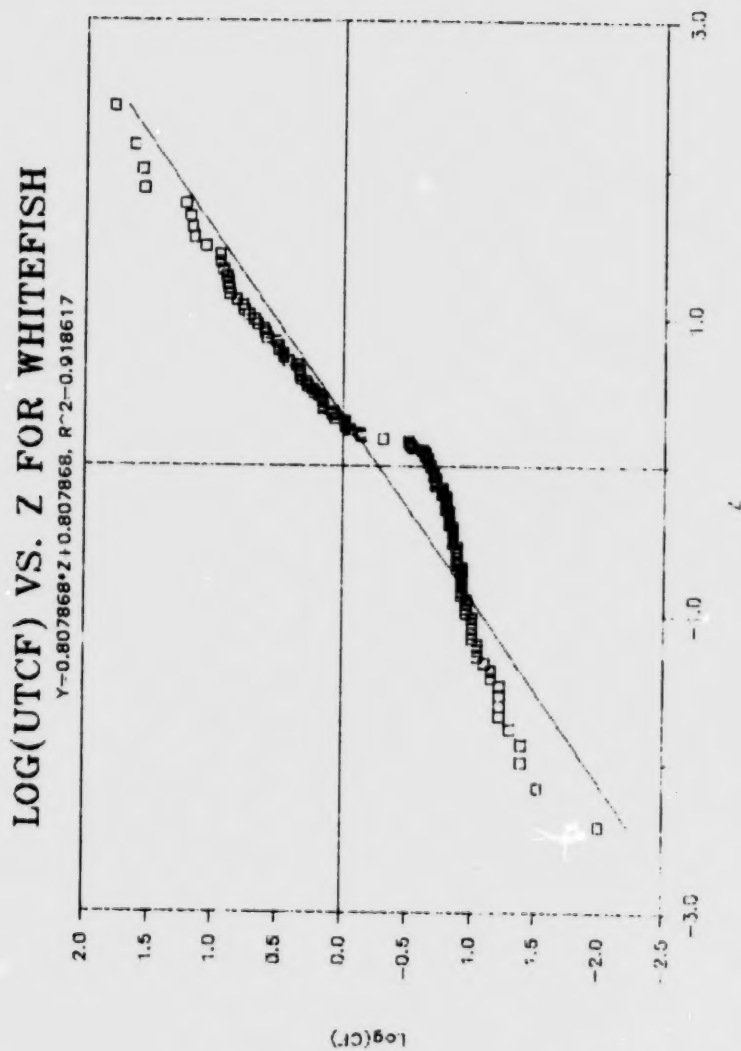


Figure D2.2c

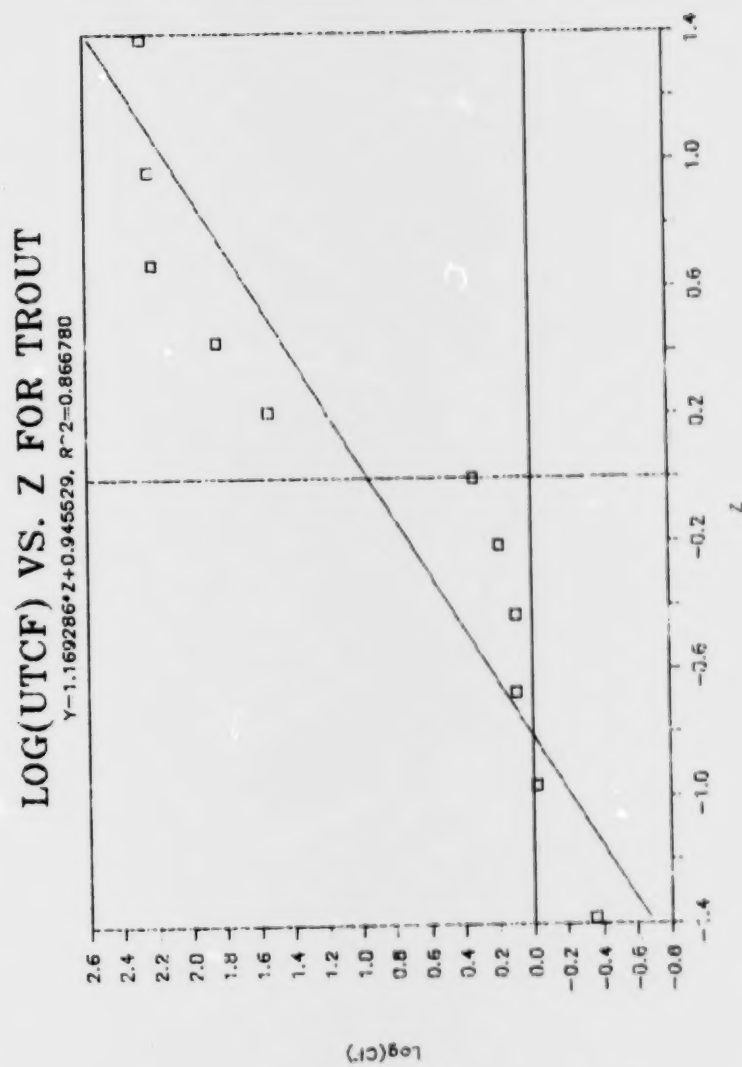


Figure D2.2d

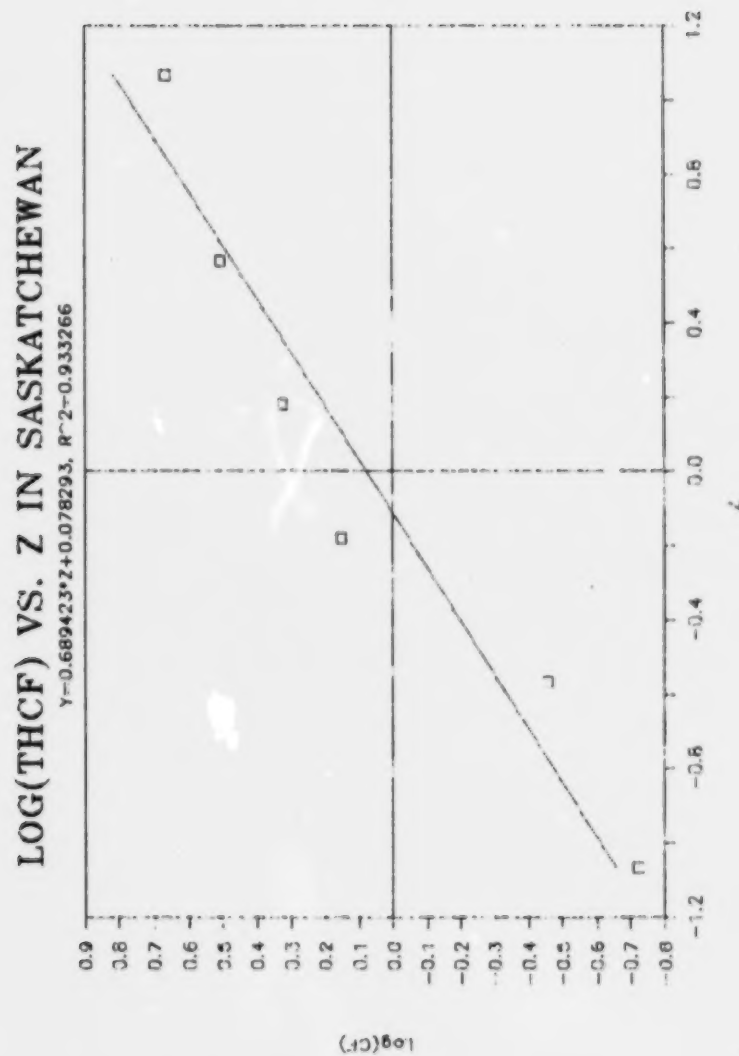


Figure D2.2e

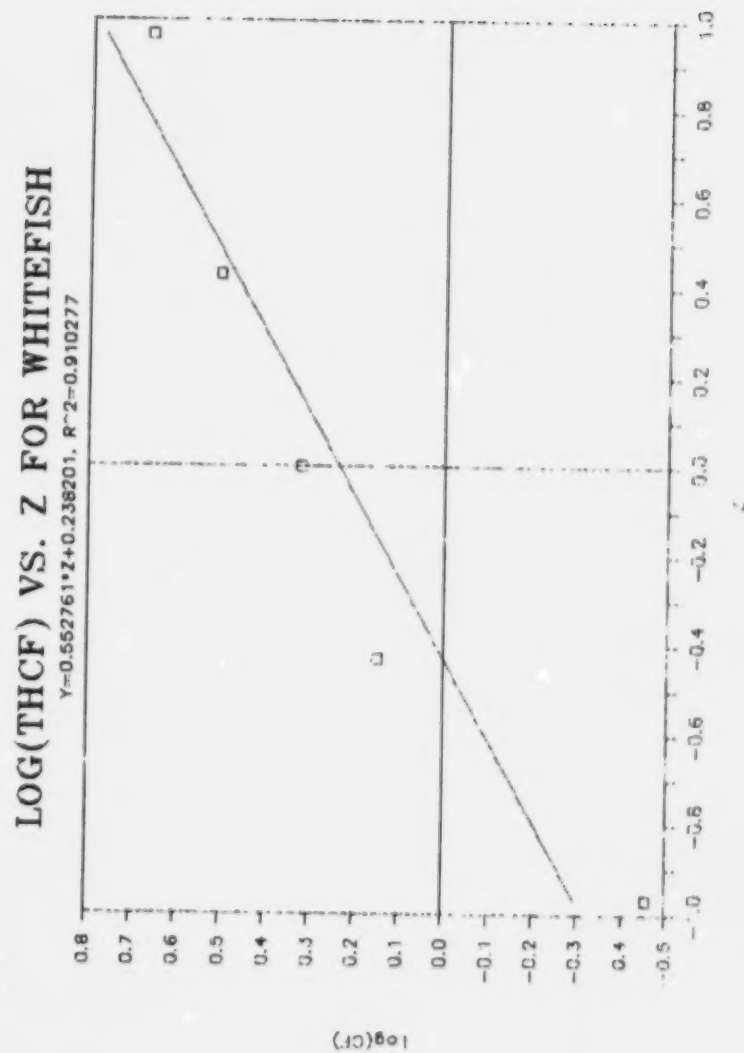


Figure D2.2f

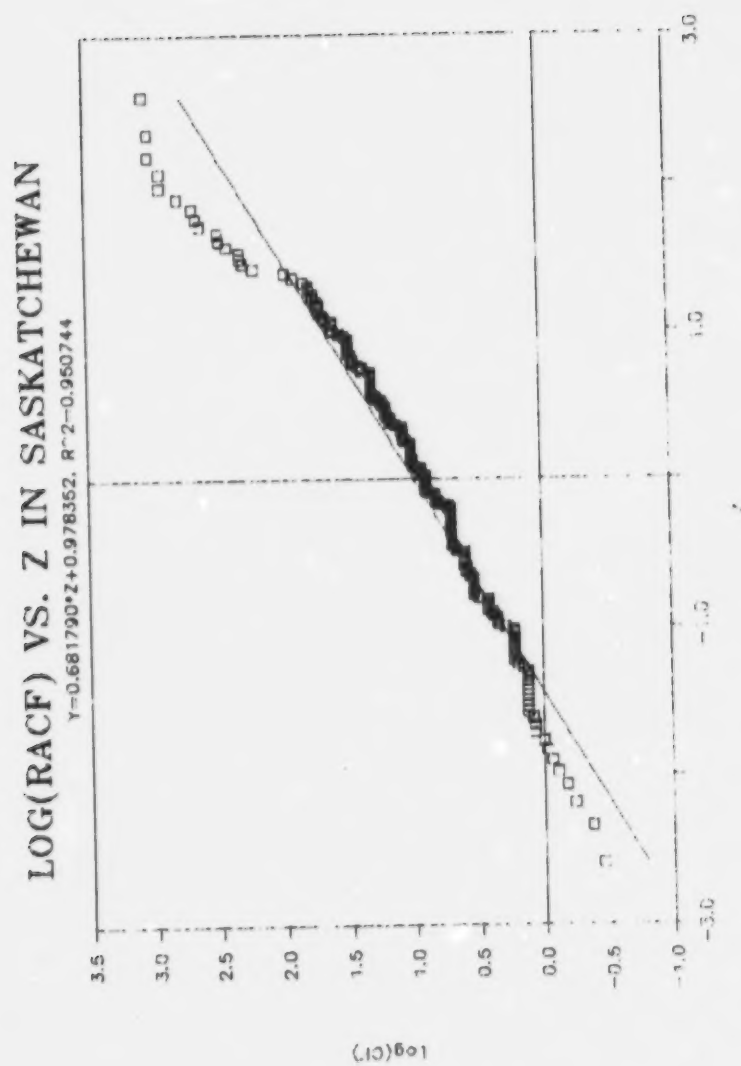


Figure D2.2g

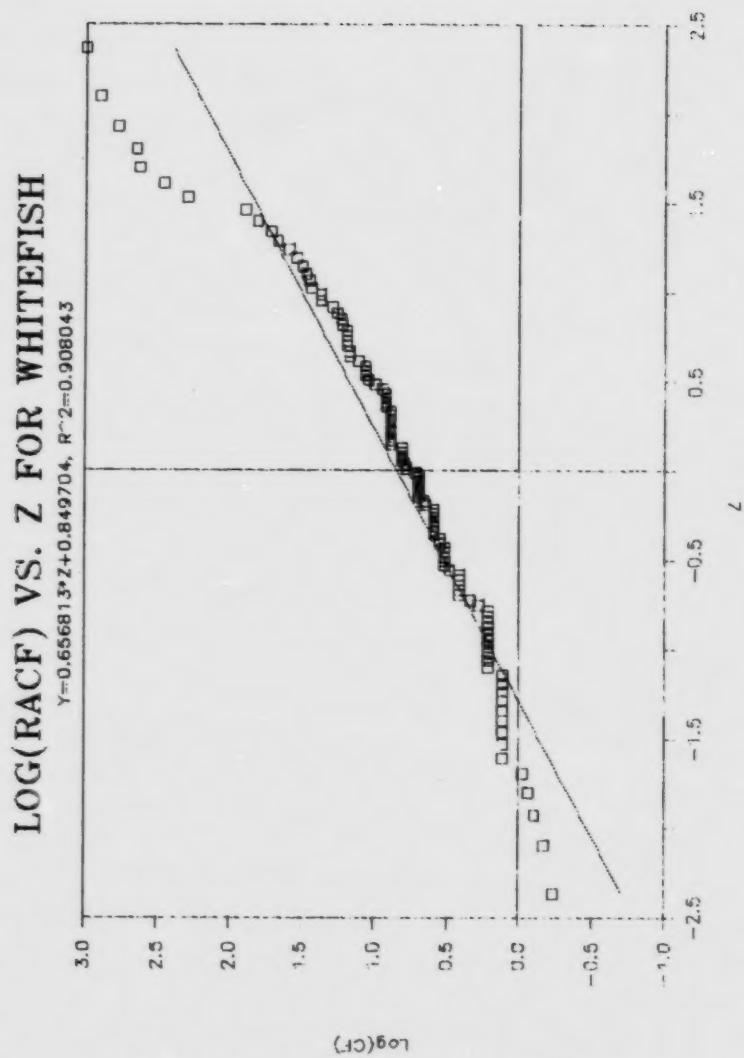


Figure D2.2h

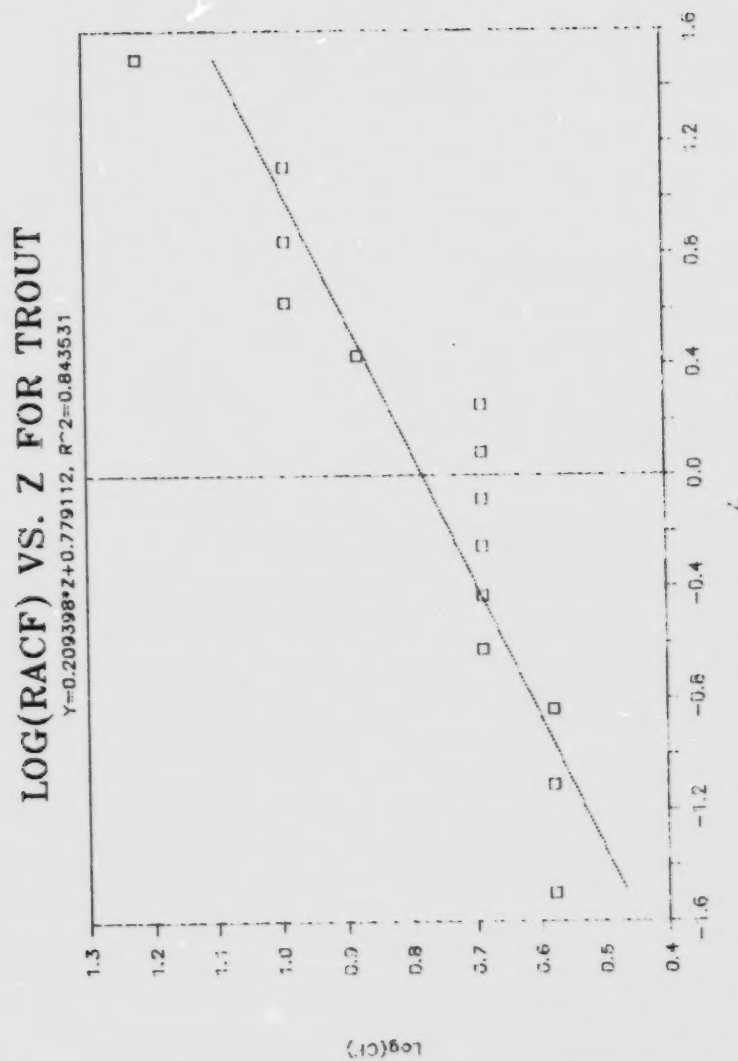


Figure D2.2i

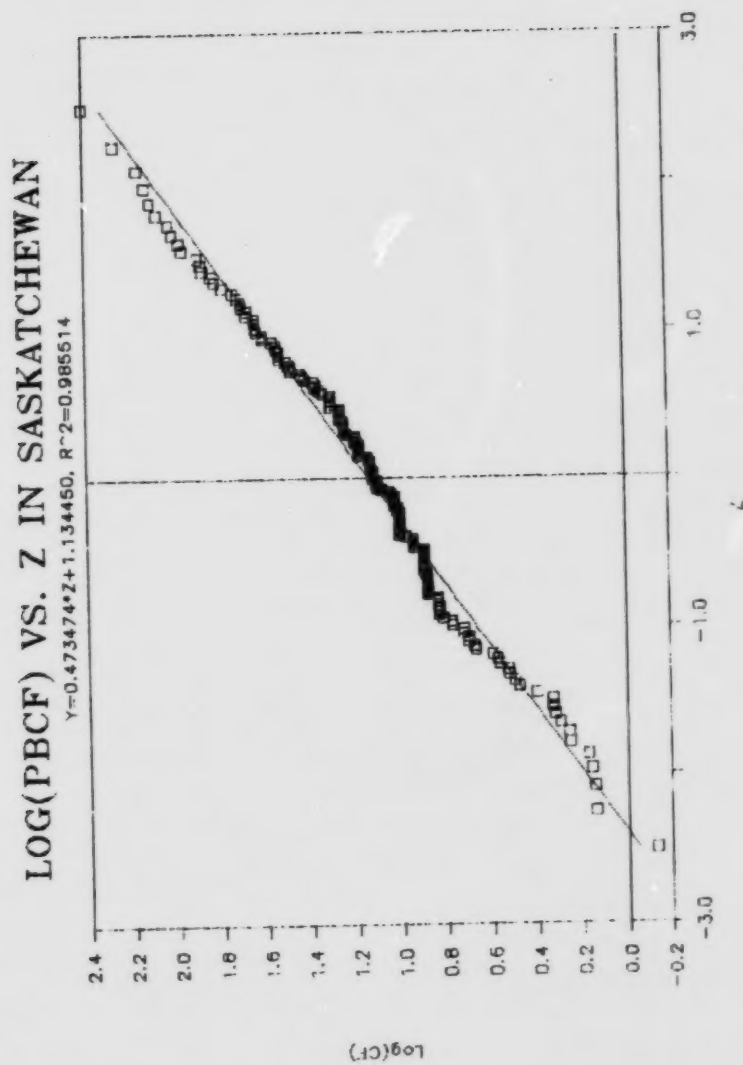


Figure D2.2j

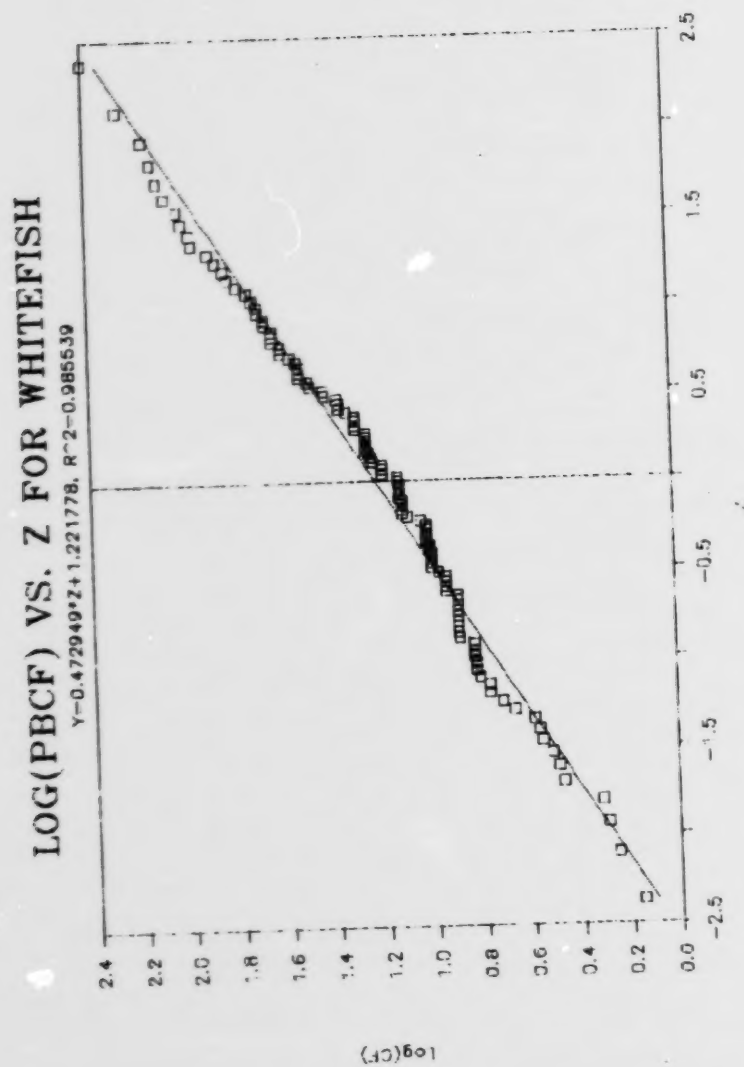


Figure D2.2k

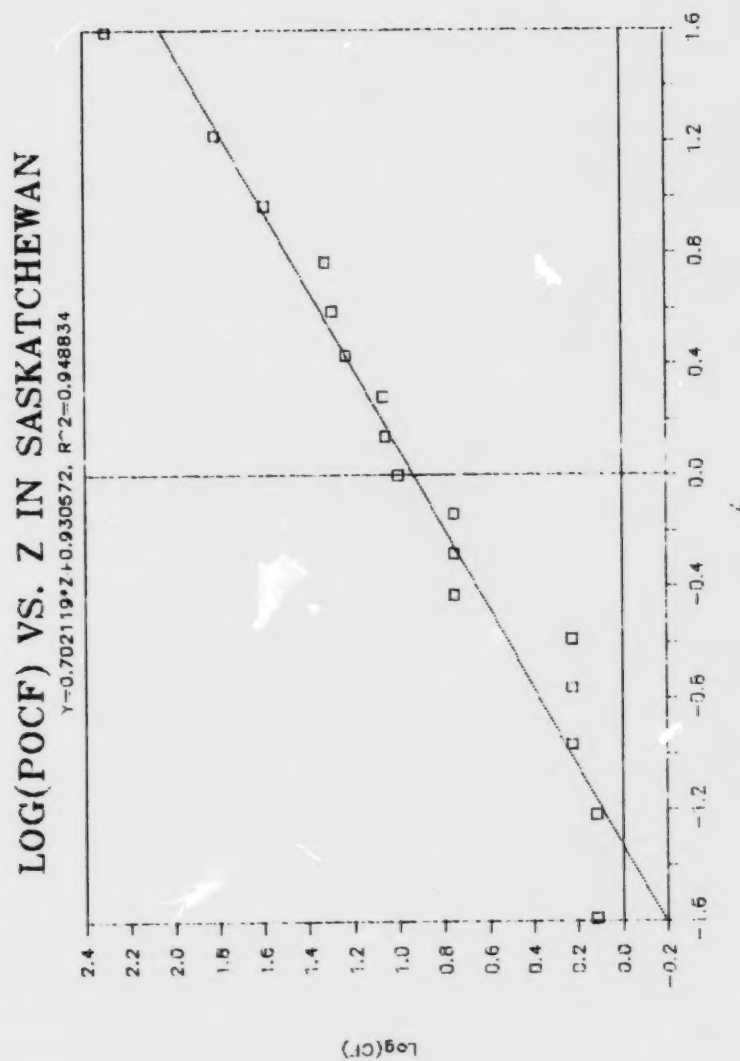


Figure D2.21

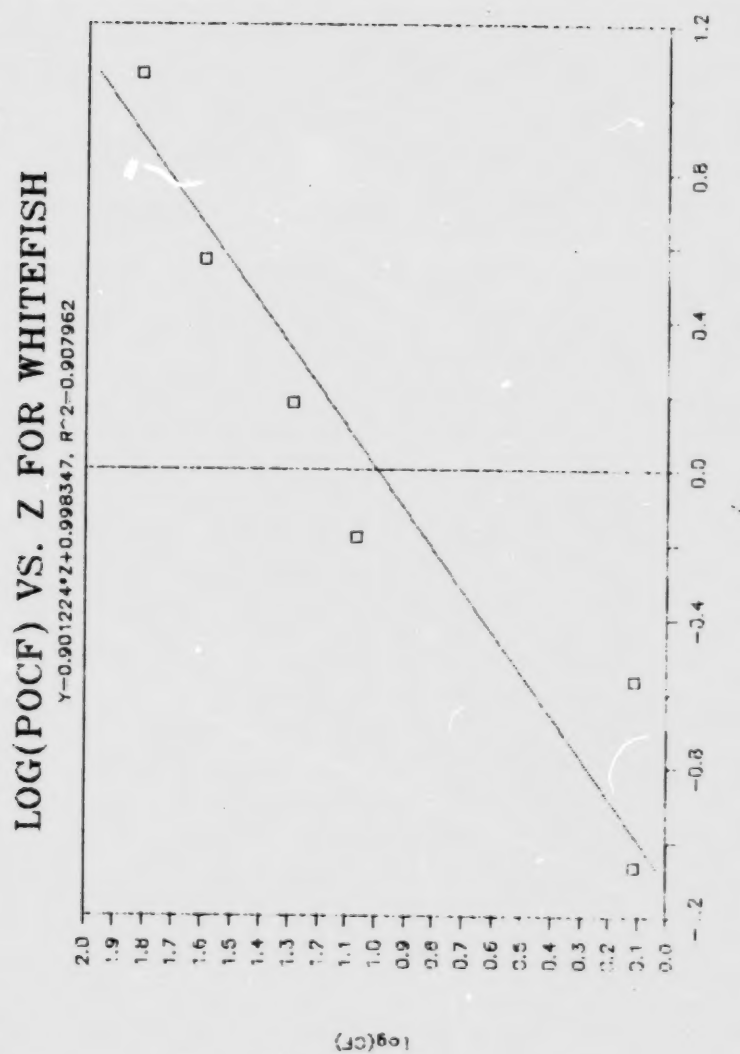


Figure D2.2m

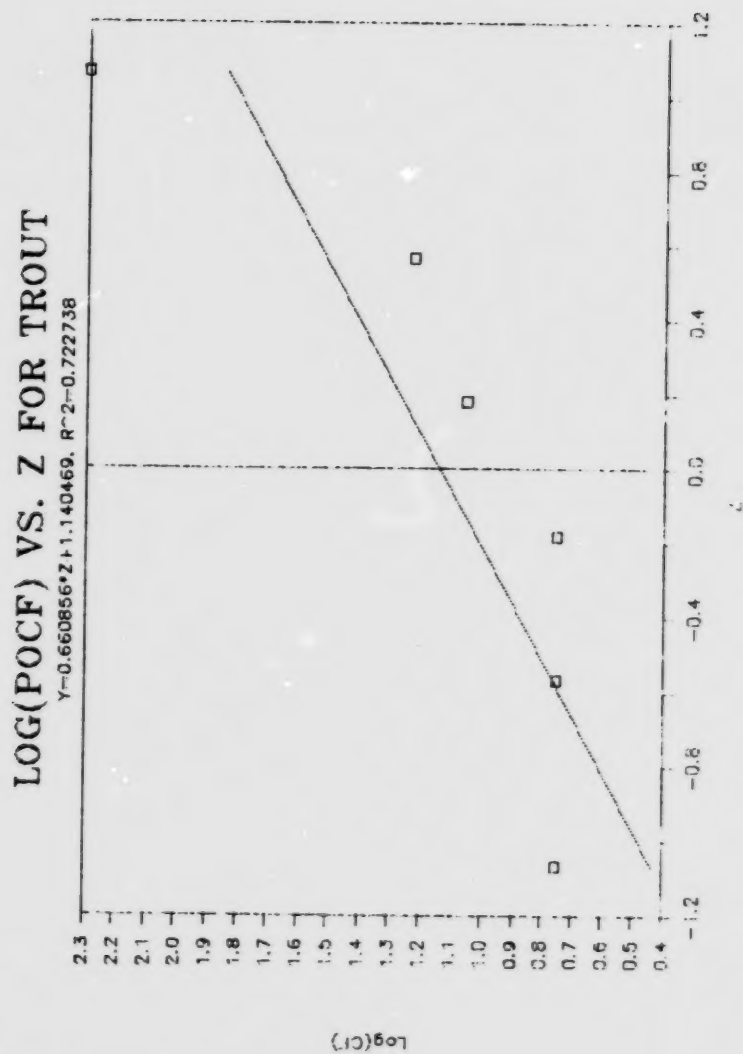


Figure D2.2n

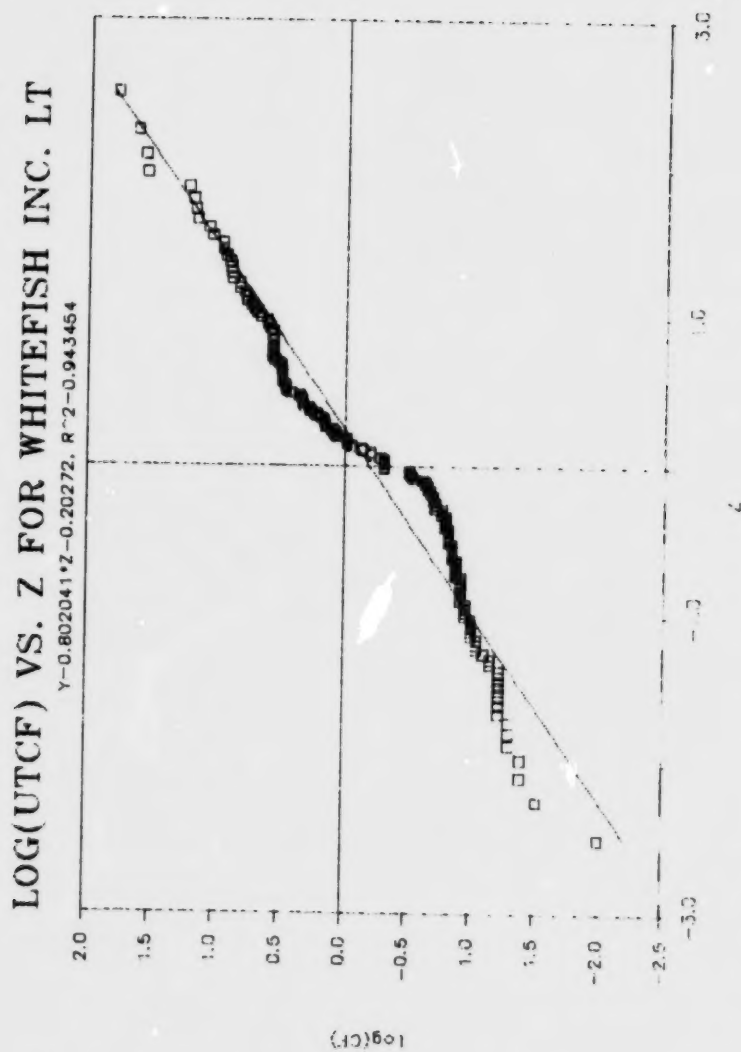


Figure D2.2o

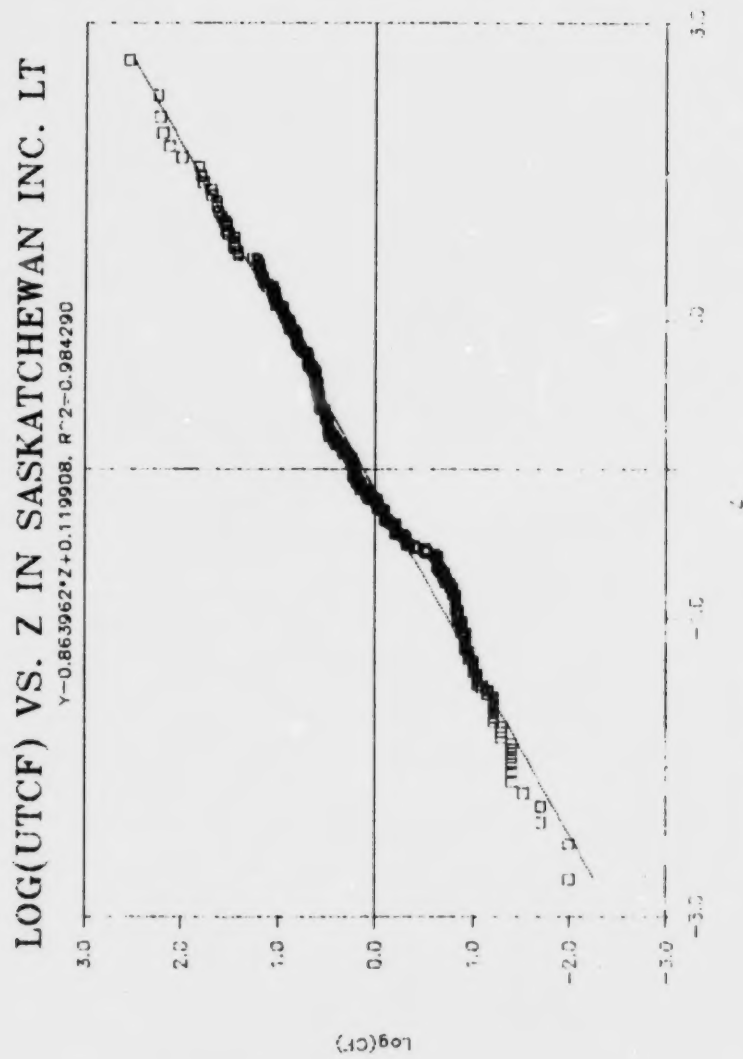


Figure D2.2p

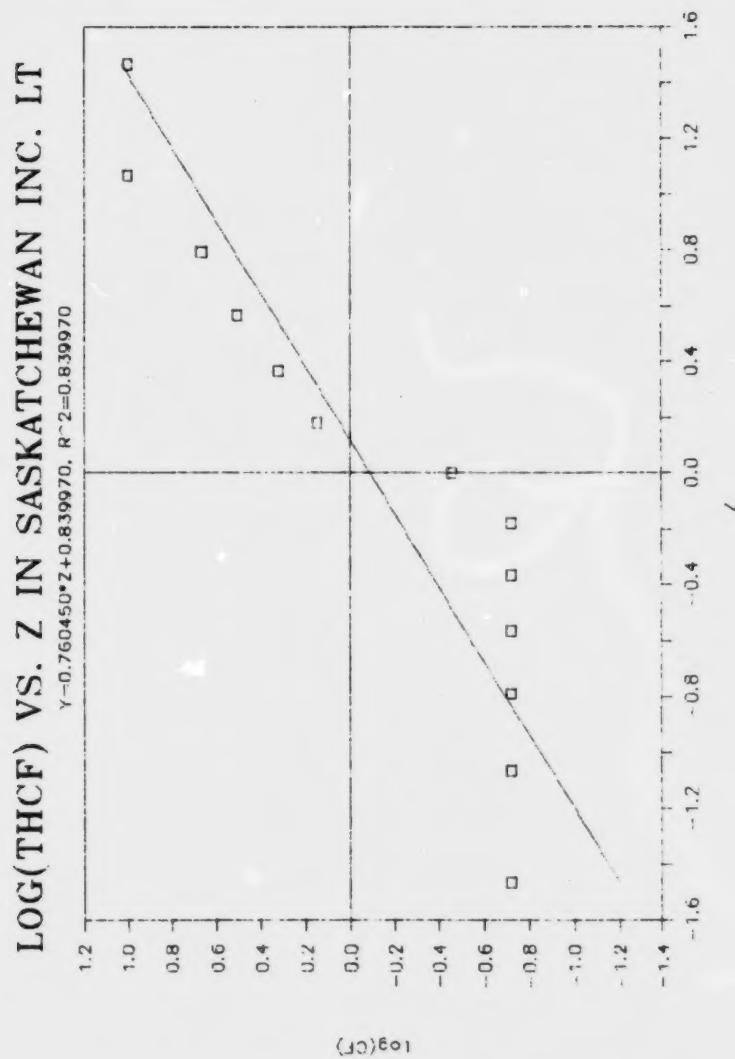


Figure D2.2q

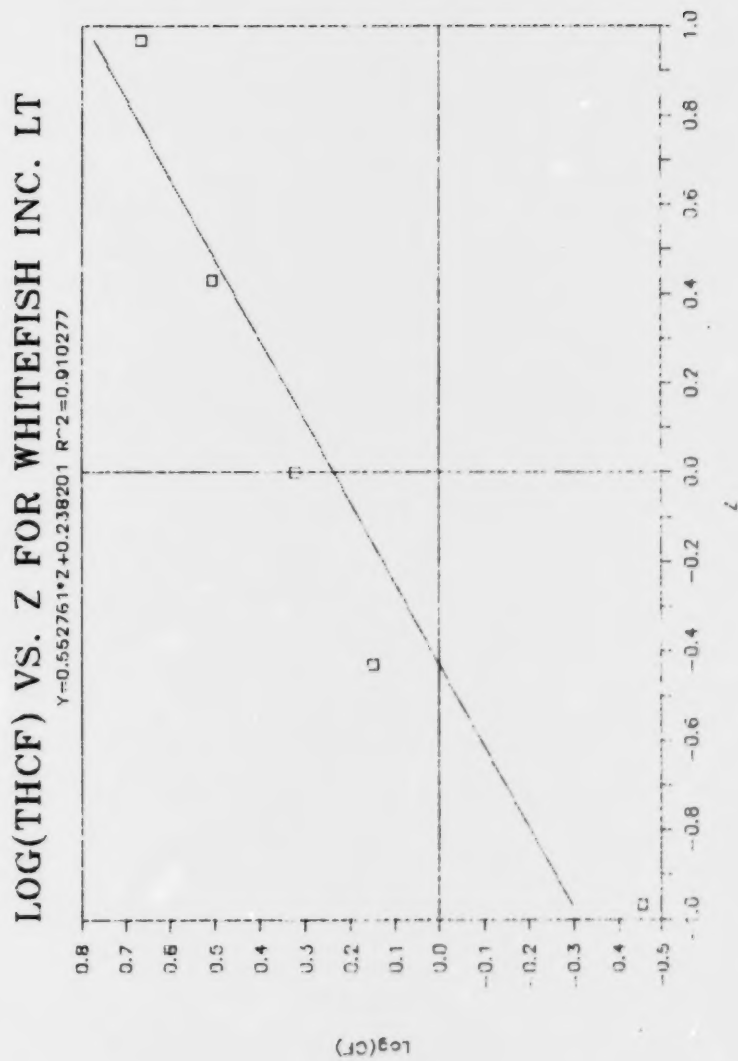


Figure D2.2r

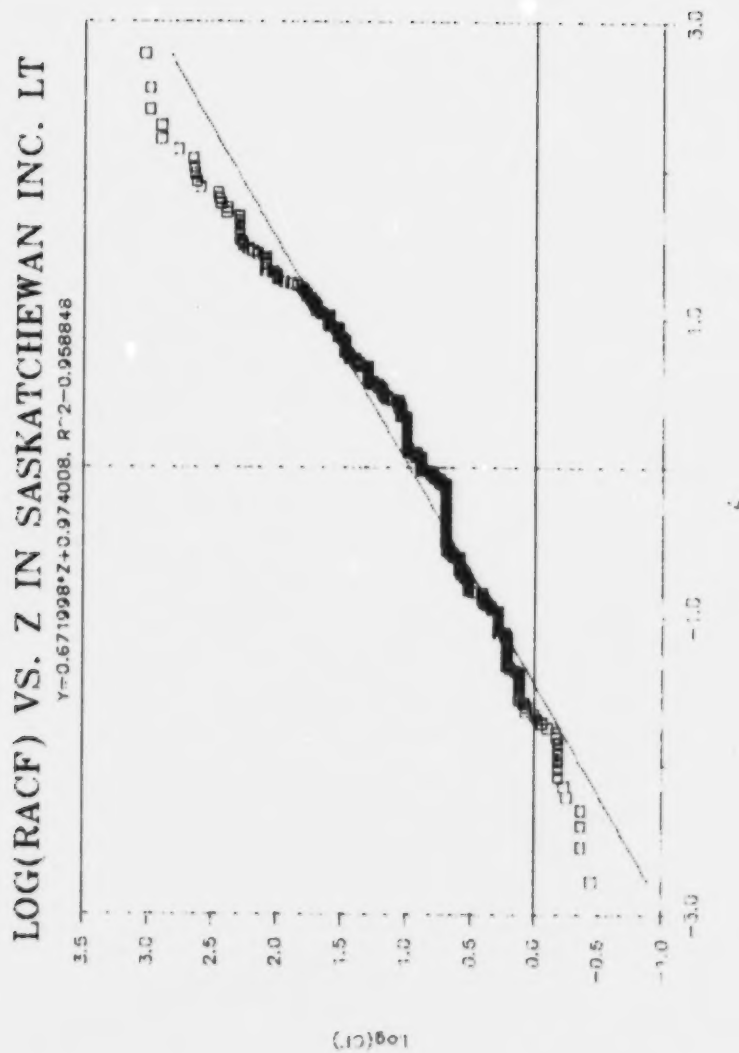


Figure D2.2s

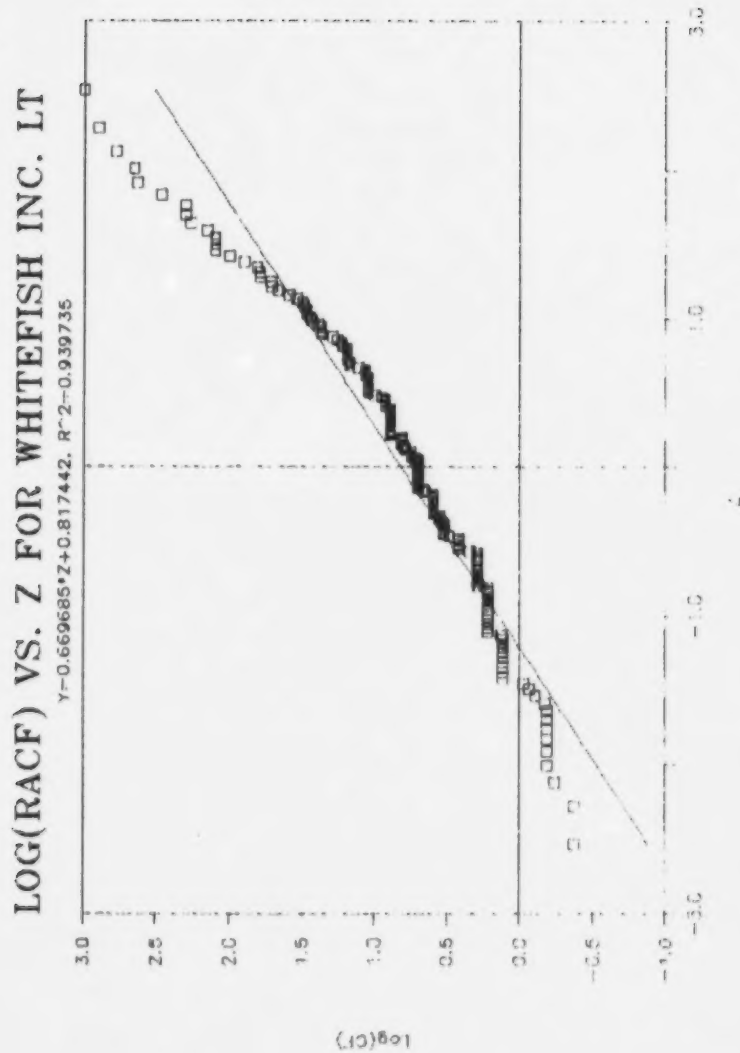


Figure D2.2t

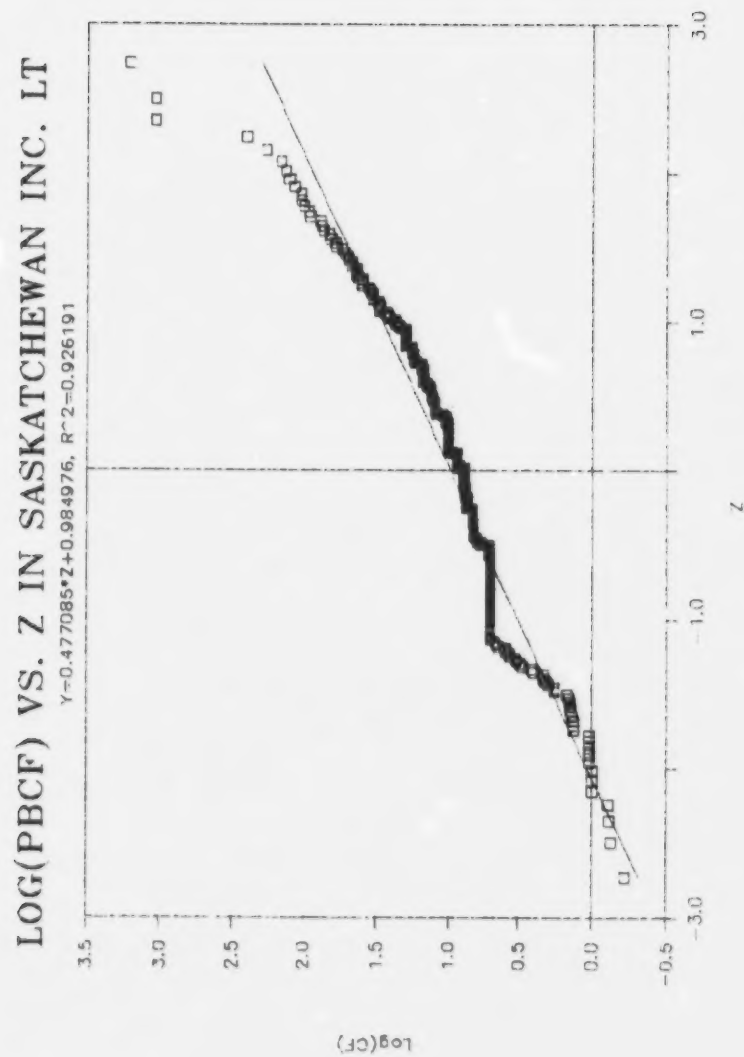
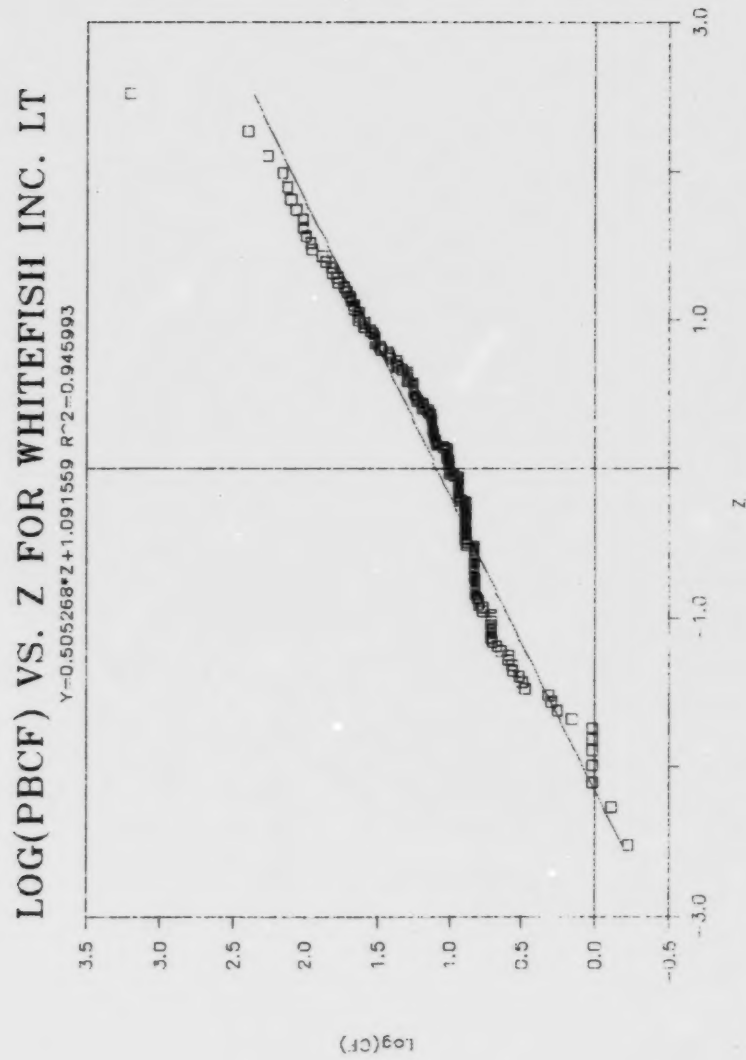


Figure D2.2u



The lakes available for the WARDS analysis and the average BCF values for uranium, radium and lead are given in Table D2.3. A blank indicates that BCF estimates are not available for a particular radionuclide in a lake. Only BCF values, which do not involve "less than" in the lake or fish values, are used in the analysis. Inspection of Table D2.3 indicates that there are various lakes which do not have BCF values for one or more radionuclides. Several lakes do not have any BCF values which do not indicate "less than's". To conduct a cluster analysis, a lake must have BCF values for radionuclides. This reduces the data set available to ten lakes. Analysis of the results (see Figure D2.3) indicate that the lakes cluster into the following three sets:

Group	
<u>No.</u>	<u>Lakes included in Group</u>
7	Delta, Gunnar Pit, Athabasca, Horseshoe, Beaverlodge, Milliken
2	Cluff, McDonald, Key
3	Fredette

The results and log normal probability plots for these three groups are given in Figure D2.4. The associated statistics are given in Table D2.3. The results indicate that segregation of the lakes into the three groups change the geometric mean somewhat. For example, the BCF for Group 2 (Cluff, McDonald and Key Lakes) of uranium and radium increases and of Pb-210 decreases compared to that for Group 1. However, the geometric mean of Group 1 has not changed substantially compared to the data (see Table D2.2).

Accordingly, further work is required in analyzing the data to attempt to narrow the range associated with estimates of BCF values. For this project, the BCF values from the whole database are retained.

D2.2.3 Sources of Data Used for Database

Amok. 1976. Environmental assessment and safety report for Amok Limited uranium project, Cluff Lake, Saskatchewan. Stearns-Roger Incorporated, Environmental Sciences Division. (22)

Beak Consultants Limited (BEAK). 1979. Key Lake Project Environmental Impact Assessment. Vol. 1 and 2. (18)

FIGURE D2.3: CLUSTER OF BCF GT ZERO WITH SEUCLID AND WARD

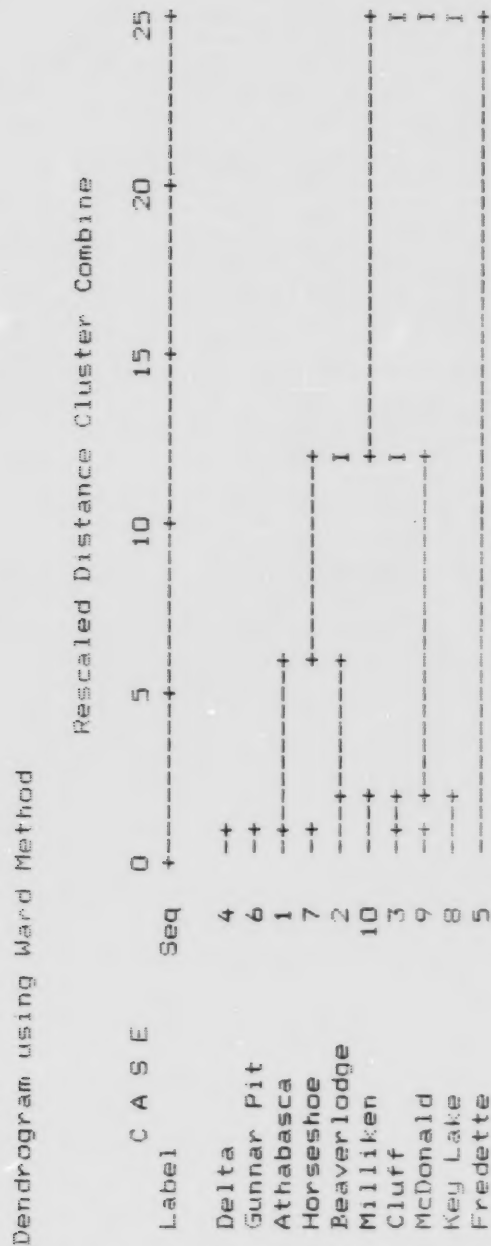
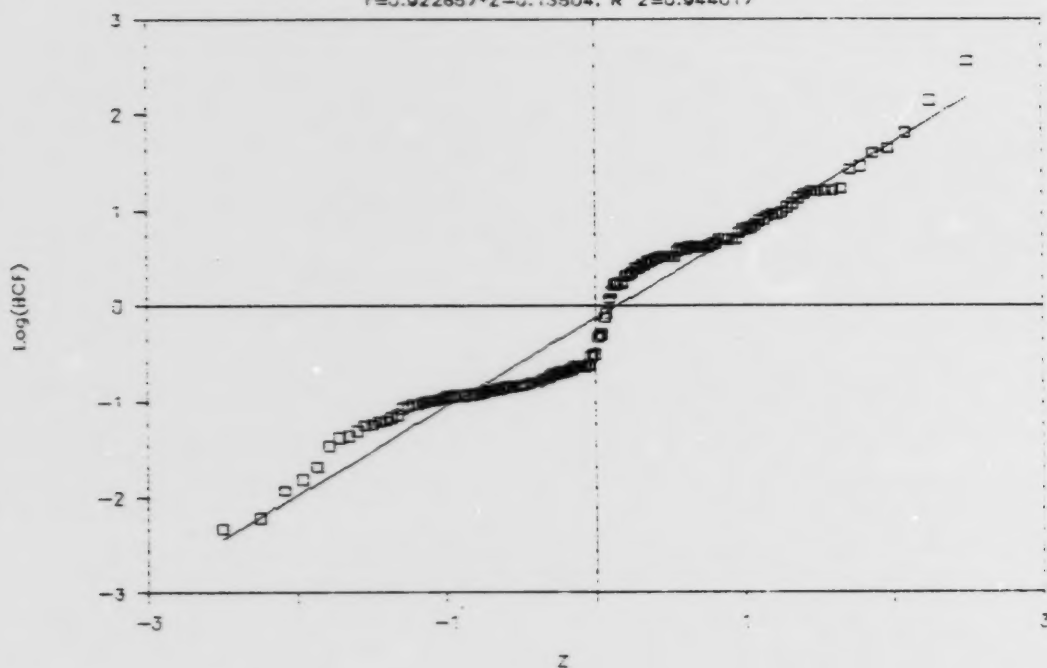


Figure D2.4a

LOG(UTCF) VS Z FOR GT ZERO, GROUP ONE

$$Y=0.922657 \cdot Z - 0.13504, R^2=0.944017$$



LOG(RACF) VS Z FOR GT ZERO, GROUP ONE

$$Y=0.627352 \cdot Z + 0.842726, R^2=0.958737$$

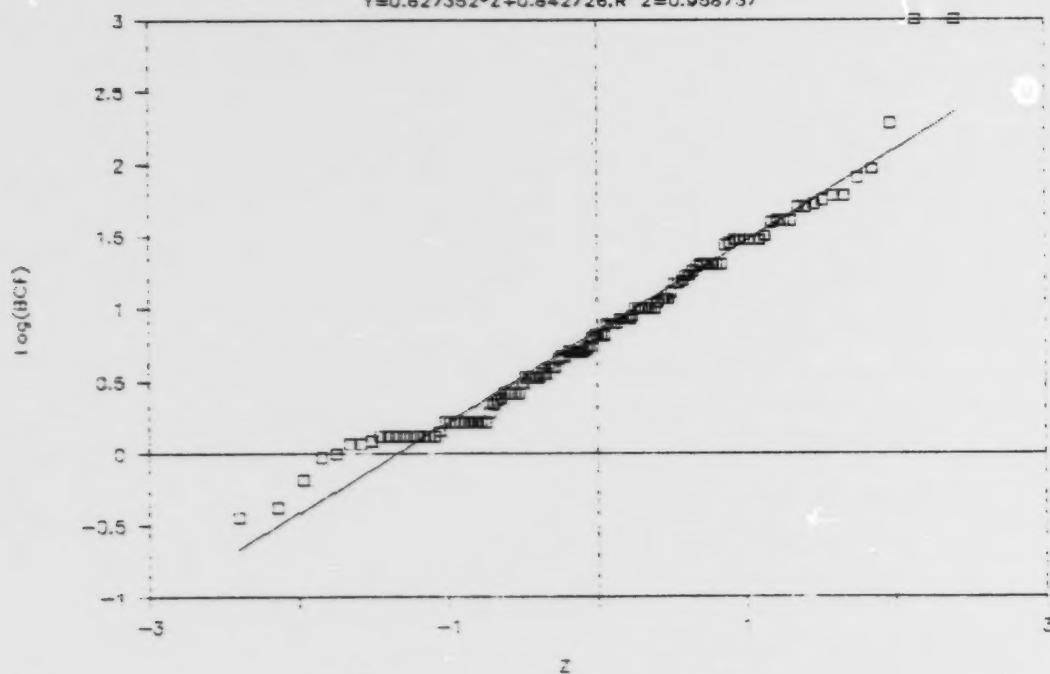


Figure D2.4b

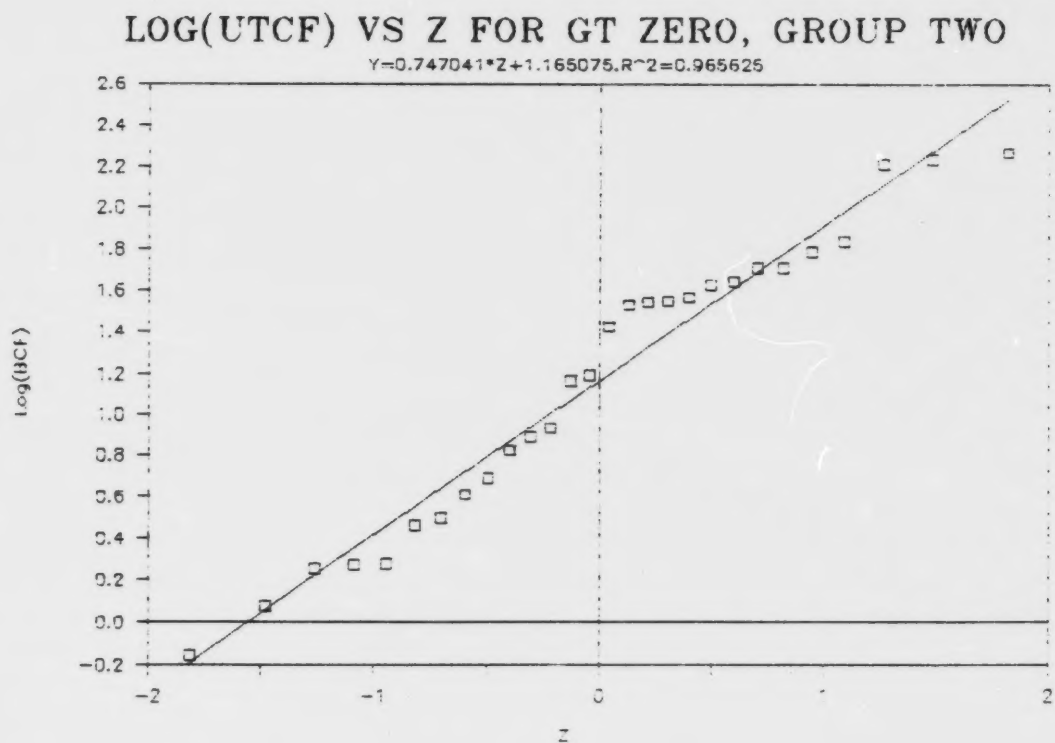
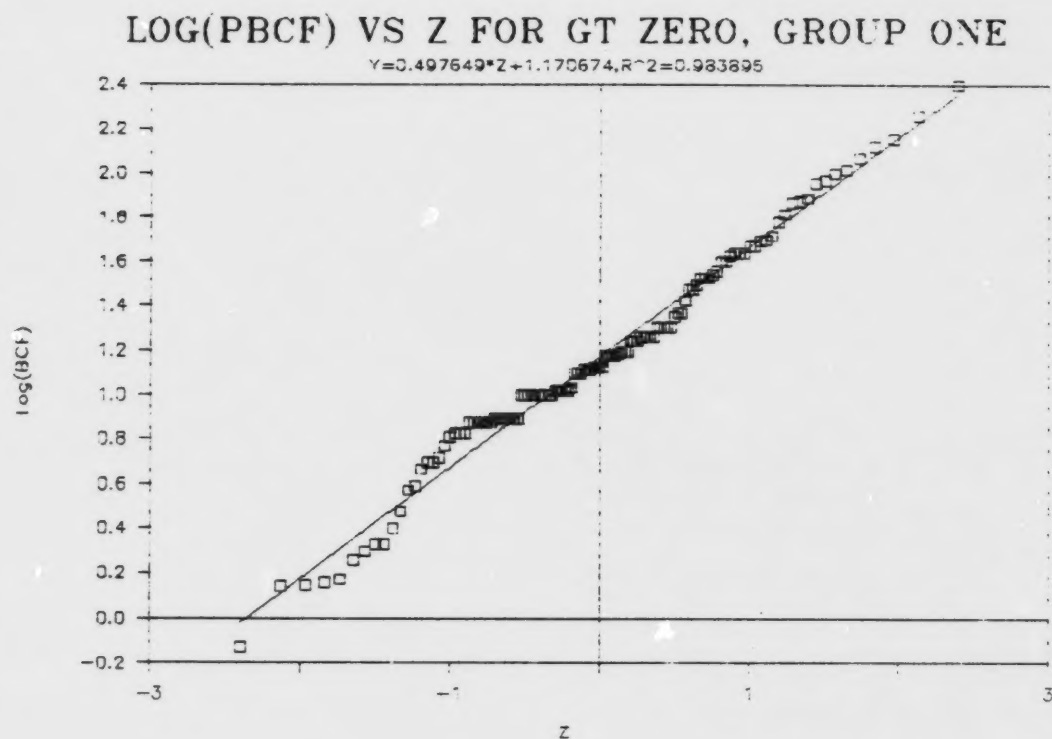


Figure D2.4c

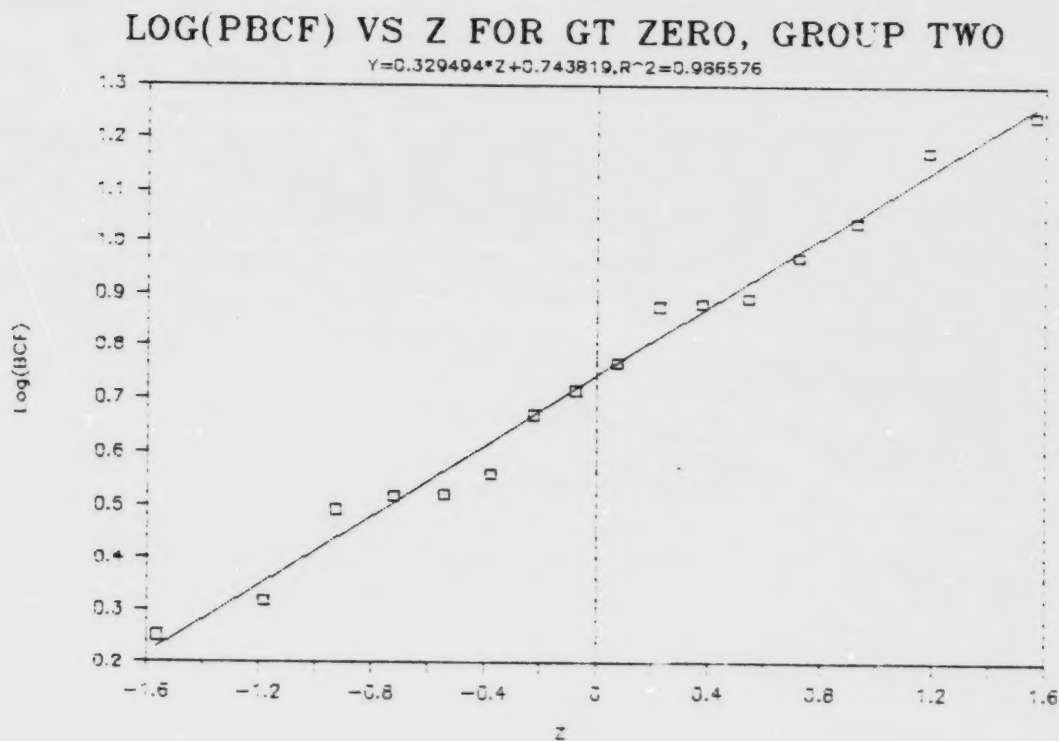
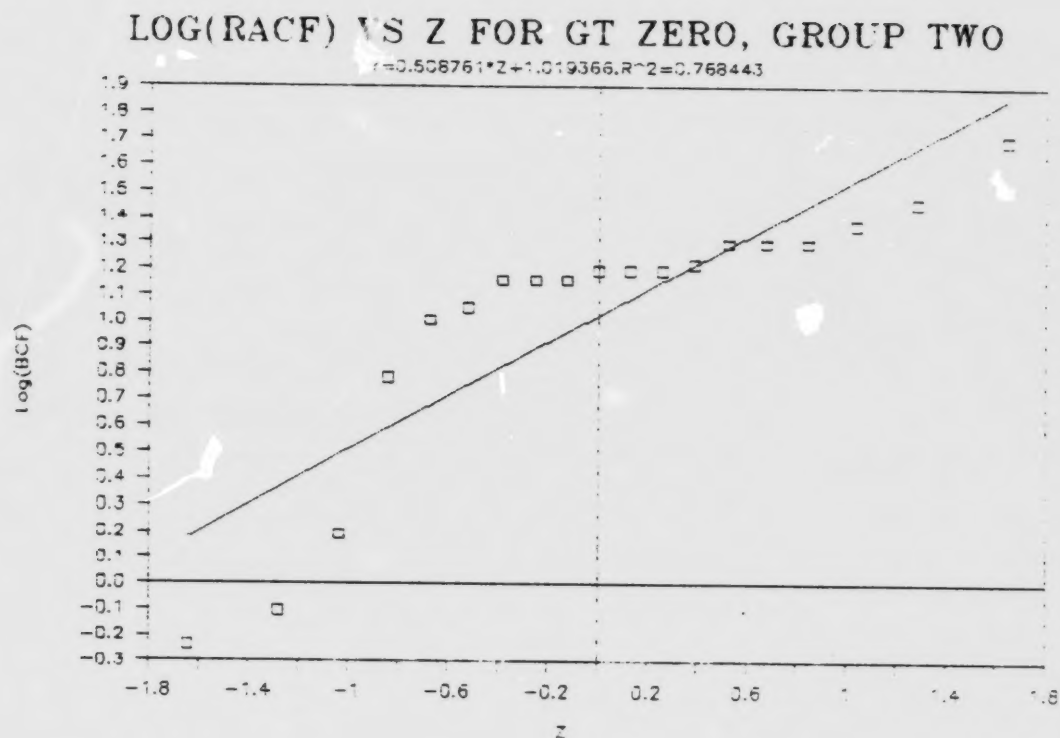
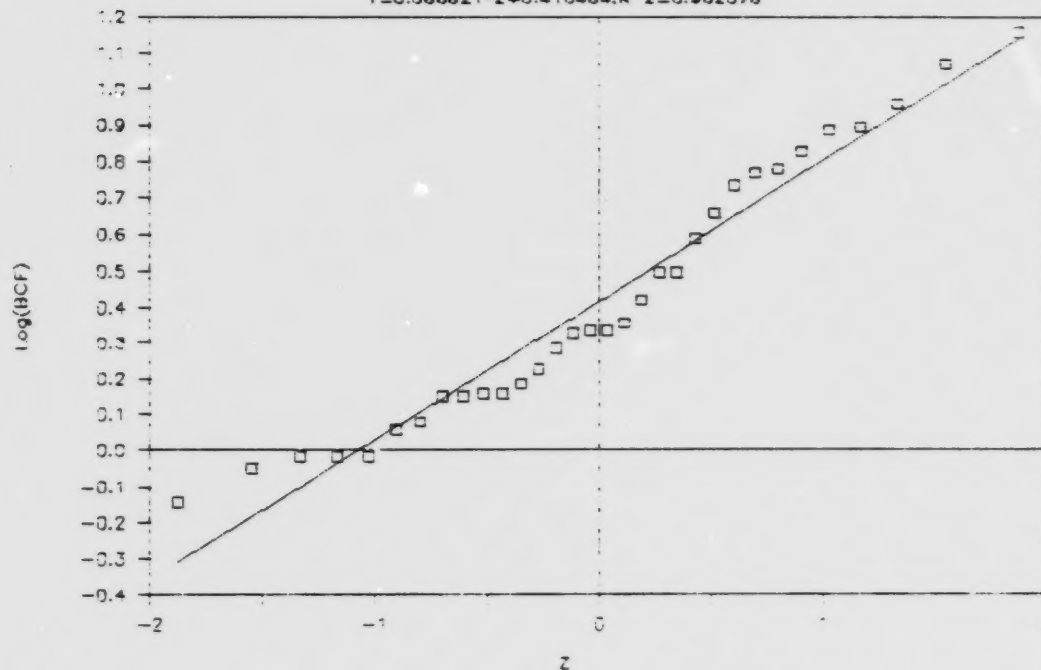


Figure D2.4d

LOG(UTCF) VS Z FOR GT ZERO, GROUP THREE

$$Y=0.386821 \cdot Z+0.415484, R^2=0.962378$$



LOG(RACF) VS Z FOR GT ZERO, GROUP THREE

$$Y=0.820516 \cdot Z+1.391319, R^2=0.907523$$

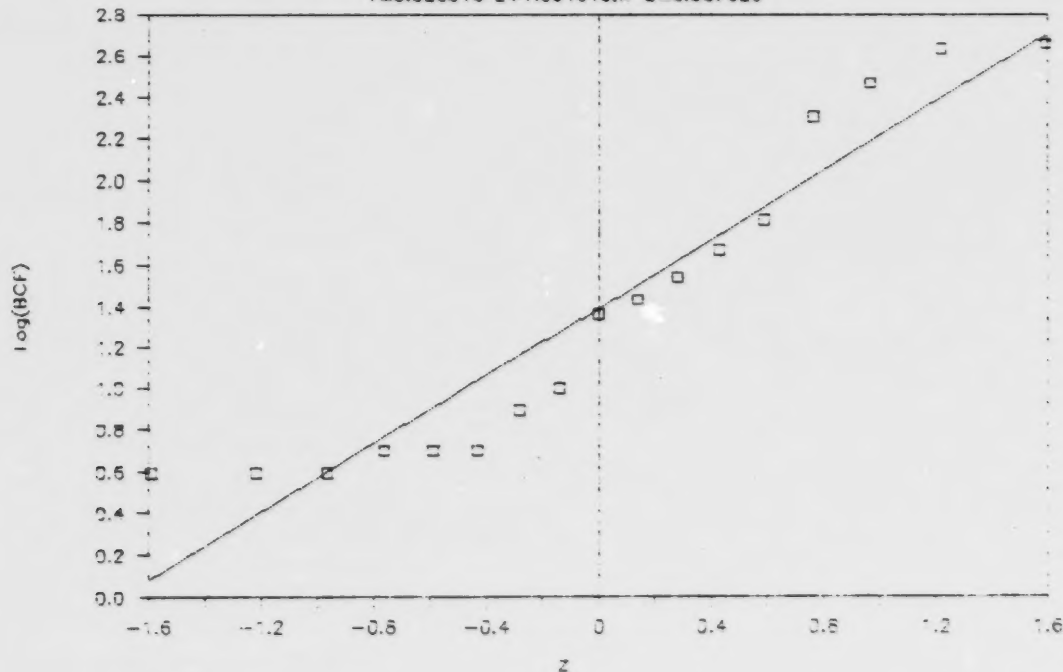


Figure D2.4e

LOG(PBCF) VS Z FOR GT ZERO, GROUP THREE

$$Y=0.371470 \cdot Z+1.225170, R^2=0.914481$$

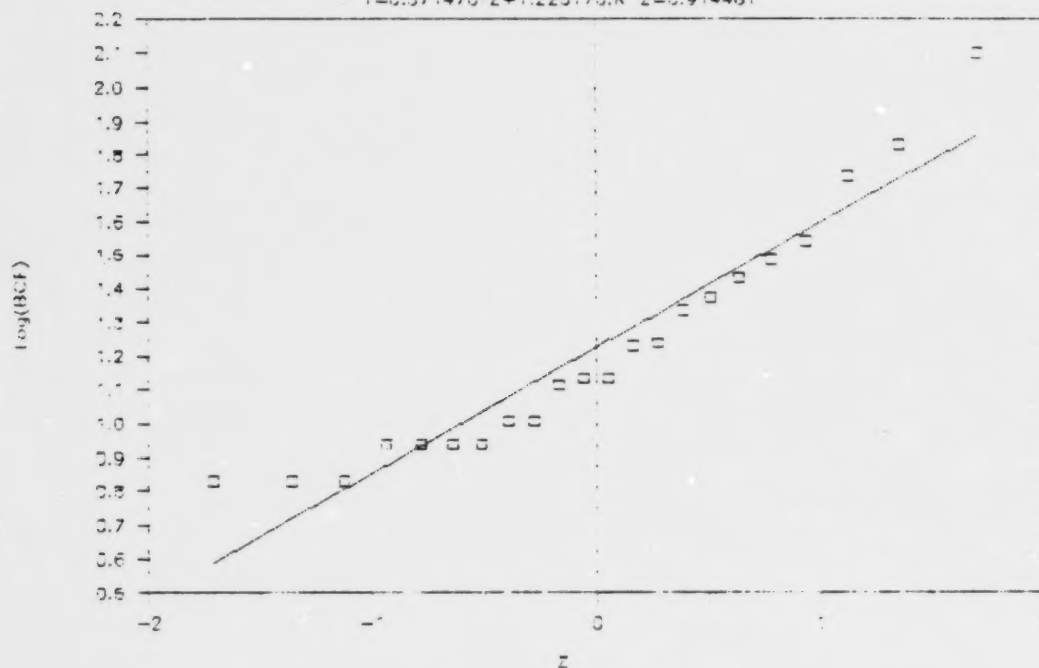


TABLE D2.3: AVERAGE BCF VALUES (GT ONLY) USED IN WARDS CLUSTER ANALYSIS

LAKE	AVGUT	AVGRA	AVGPB
Athabasca	2.75	2.12	3.33
Beaverlodge	2.16	36.42	38.31
C1	.	.	.
Cluff	31.09	16.83	4.37
Collins Creek	.	200.00	.
Cumberland	.	.	.
Delta	1.70	5.34	9.40
Donaldson	1.55	4.72	.
Dubyna	.49	9.84	.
Fredette	3.70	95.21	24.36
Fulton	101.92	1081.08	.
Gunnar Pit	.02	1.57	10.26
Hatchet	.	.	.
Henday	.	800.00	.
Horseshoe	11.27	8.20	4.03
Island	.	.	.
Kewen	.	.	14.57
Key Lake	45.66	.97	7.14
McClean	.	30.34	.
McDonald	42.50	19.67	8.54
McMahon	.	500.00	.
Midwest	.	.	.
Milliken	13.98	35.56	16.53
Russell	2.60	.	.
Sandy	.	.	.
Schmoo	.	6.80	.
Shallow	.	285.71	.
Snake	.	.	.
W1	.	157.89	.
Waterbury	.	.	.
Wheeler R.	.	9.57	.
Wollaston	.	116.47	.

Number of cases read = 32

TABLE D2.4: STATISTICS OF ANALYSIS OF BCF VALUES BY LAKE GROUPS

Group	Uranium		Ra-226		Pb-210	
	Log BCF	± 1 Log SD	Log BCF	± 1 Log SD	Log BCF	± 1 Log SD
Log Units						
1	-0.135	(-1.057, 0.787)	0.842	(0.215, 1.47)	1.17	(0.673, 1.67)
2	1.16	(0.413, 1.91)	1.02	(0.51, 1.53)	0.744	(0.415, 1.07)
3	0.415	(0.030, 0.802)	1.39	(0.57, 2.21)	1.22	(0.85, 1.59)
Normal Units						
	<u>BCF</u>	<u>SD Range</u>	<u>BCF</u>	<u>SD Range</u>	<u>BCF</u>	<u>SD Range</u>
1	0.73	(0.087, 6.1)	7.0	(1.6, 30)	15	(4.7, 47)
2	14	(2.6, 81)	10	(3.2, 34)	5.5	(1.4, 12)
3	2.6	(1.1, 6.3)	25	(3.7, 160)	17	(7.1, 39)

- Beak Consultants Limited (BEAK). 1980. Midwest Lake environmental baseline study. Report for Canada Wide Mines Ltd. (1)
- Beak Consultants Limited (BEAK). 1985. Benthological, Chemical, Radiological and Chronological Evaluation of Sediments in Port Hope Harbour. (12)
- Cluff Lake Uranium Mine. 1983. Annual Report. (25)
- Cluff Lake Uranium Mine. 1984. Annual Report. (26)
- Cluff Lake Uranium Mine. 1985. Annual Report. (27)
- Eldor Mines. Annual Environmental Report. 1982, 1984. Rabbit Lake Mine. (29)
- Eldorado Mine. 1986. Project review, Collins Bay, A-Zone, D-Zone and Eagle Point Development. Rabbit Lake Operations, May 1986. (30)
- EPS. 1983. Analysis of fish samples from Great Bear Lake (D. Southerland, personal communications). (15)
- EPS. 1986. Analysis of fish from Langley Bay, Lake Athabasca (D. Waite, personal communications). (35)
- Gulf Minerals Canada Ltd. 1980. Environmental impact statement, Collins Bay, B-zone development, Rabbit Lake operations. Vol. 1,3. Summary Statement. (31)
- Hesslein, R.H. and E. Slavicek. 1984. Geochemical pathways and biological uptake of radium in small Canadian Shield lakes. Can. J. Fish. Aquat. Sci. 41: 459-468. (32)
- Integrated Environmental Sciences Inc. 1983. Baseline studies of aquatic sediments and macrophytes, fish, soil and terrestrial vegetation at Key Lake, Saskatchewan. Prepared for Key Lake Mining Corporation. (7)
- Kalin, M. 1984. Rayrock Northwest Territories uranium tailings and environment. Institute for Environmental Studies. University of Toronto. EPS Contract OSG83-00074. (33)
- Key Lake Mining Corporation. Environmental and hydrological monthly monitoring reports. 1983, 1984, 1985. (19)
- Key Lake Mining Corporation. 1985. Environmental year end monitoring report. (20).
- NUTP. 1985. A fish study for the National Uranium Tailings Program. NUTP-85-4(TR). (10)
- Norcen. 1980. Blizzard uranium property baseline environmental studies. (21)
- Robinson, D.J., R.G. Ruggles and A. Zaidi. 1983. A study of water pollution in the vicinity of Gulf Minerals, Rabbit Lake, 1978. Surveillance Report EPS-5-W and NR-83-1. (5)
- Ruggles, R.G. and W.J. Rowley. 1978. A study of water pollution in the vicinity of Eldorado Nuclear Limited, Beaverlodge operation 1976 and 1977. Report EPS-5-NW-78-10. (8)

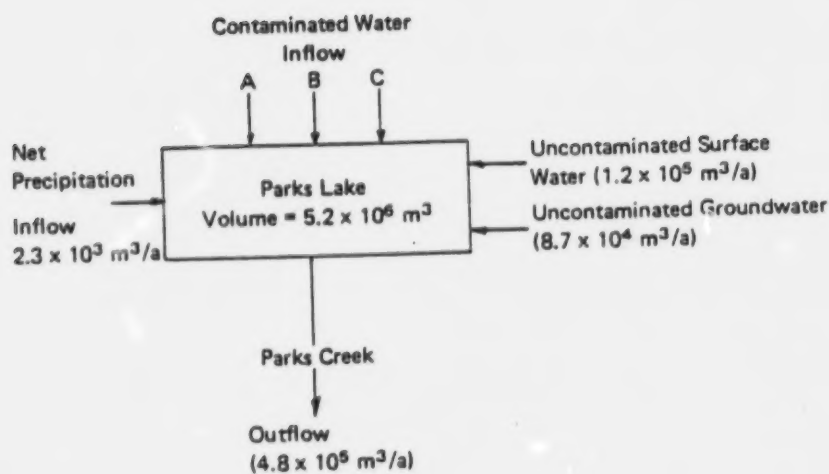
- Ruggles, R.G., D.J. Robinson and A. Zaidi. 1981. A study of water pollution in the vicinity of two abandoned uranium mills in northern Saskatchewan, 1978. Report EPS-WNR-5-81-2. (6)
- SRC. 1978. Environmental overview assessment for the Dubyna 31-zone uranium productions program. Report for Eldorado Nuclear Limited. (28)
- SRC. 1979. Additional baseline studies for the Cluff Lake area. (24)
- SRC. 1982. Cluff Lake Development. Phase II. Environmental Impact Assessment. November 1982. (23)
- Swanson, S. 1982. Levels and effects of radionuclides in aquatic fauna of the Beaverlodge area (Saskatchewan). SRC Publication C-806-5-E-82. (2)
- Swanson, S. 1983. Levels of ^{226}Ra , ^{210}Pb and total U in fish near a Saskatchewan uranium mine and mill. Health Physics 45: 67-80. (4)
- Swanson, S. 1985. Food chain transfer of U-series radionuclides in a northern Saskatchewan aquatic system. Health Physics 49(5): 747-770. (3)
- Tones, P.I. 1982. Limnological and fisheries investigation of the flooded open pit at the Gunnar uranium mine. SRC Publication C-805-10-E-82. (11)

Figure D3.2

ELDOR MINES RABBIT LAKE

Figure A.2

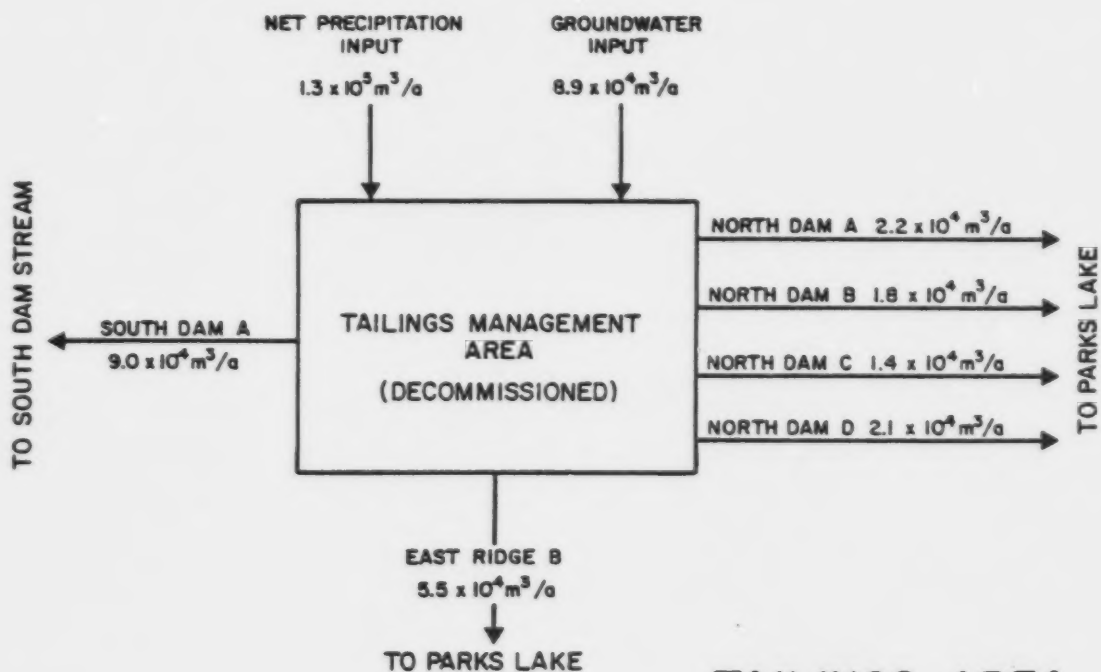
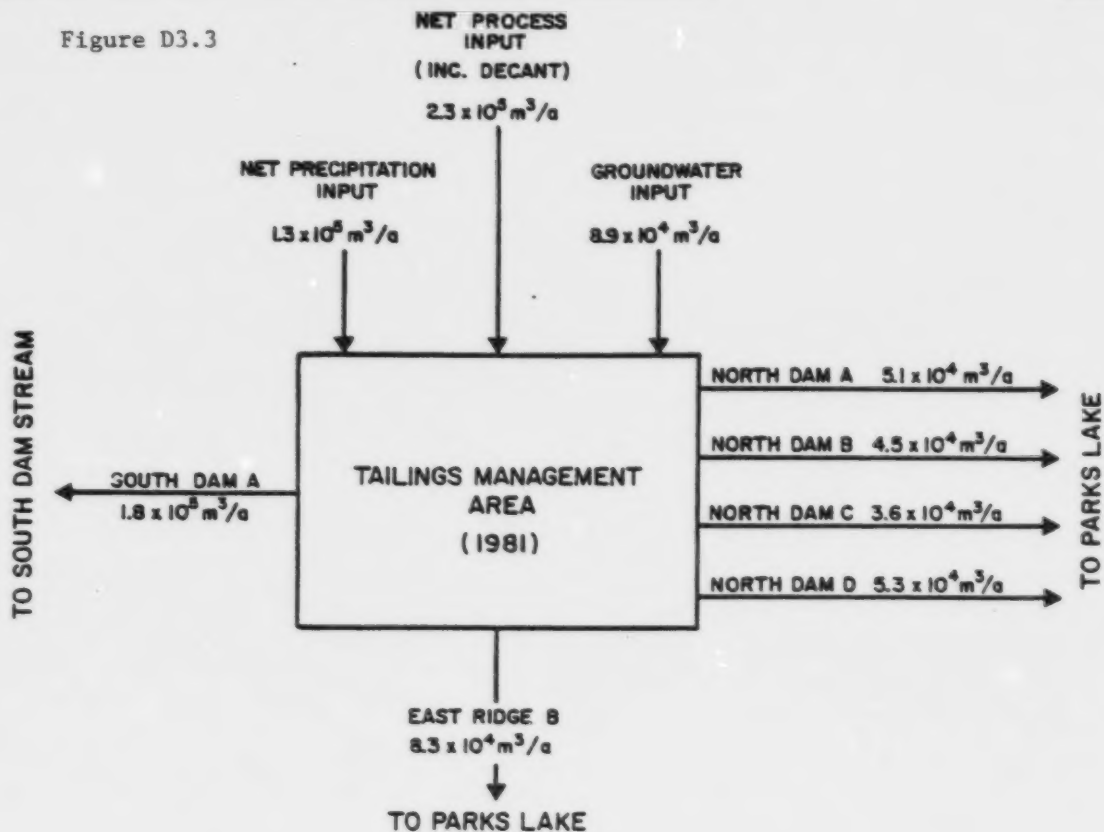
Parks Lake Water Balance (1981 Situation)



Channel A	(North Dam Toedrain Seepage)	$9.5 \times 10^4 \text{ m}^3/\text{a}$
Channel B	(North Dam Deeper Seepage)	$8.9 \times 10^4 \text{ m}^3/\text{a}$
Channel C	(East Ridge Seepage)	$8.3 \times 10^4 \text{ m}^3/\text{a}$
Total		$2.7 \times 10^5 \text{ m}^3/\text{a}$

Note: Seepages after decommissioning are expected to be following fractions of 1981 values:
 North Dam 0.4
 East Ridge 0.66

Figure D3.3



TAILINGS AREA WATER BALANCE

FIGURE A-3

APPENDIX E

Code Structure and Quality Assurance

APPENDIX E: CODE STRUCTURE AND QUALITY ASSURANCE

E.1 Code Structure

E.1.1 Time Required to Run and Modify Code

This section gives estimates of time required to run one version of UTAP on different machines as a benchmark. It also outlines the modifications required for developing an appropriate version of the UTAP code for application to Rabbit Lake.

We had already obtained the Phase II code from SENES on floppy disk. We undertook to run it as a tool for learning its code structure and its transportability. The code and data structure were run directly upon an IBM-XT and IBM-PC. The code structure was modified somewhat to accommodate running it upon the BEAK SUN microcomputer and upon a CDC mainframe.

Within approximately one week of obtaining the code, these runs were all made and we were able to ask questions of the code (such as what different results are obtained if a particular parameter has a different probability distribution). For a standard test run involving a 1,000 year simulation period and 500 simulation passes, the SENES code bench-marked at approximately 6.5 hr on the 8088 chip-based IBM-XT (with hard disk memory) and IBM-PC (without a hard disk memory) with each having an 8087 floating-point processor, 45 minutes on the SUN and 25 minutes on the CDC mainframe.

In the application to Rabbit Lake, the SENES (Phase III) version of UTAP and the BEAK (1986) version of UTAP were amalgamated. The input data structure, the loadings (source) model, the groundwater pathway modelling, the lake model and the dose models of BEAK were modified as required and used. The groundwater model of BEAK (1986) is the same as that of UTAP.3. Coding for such aspects as the tailings erosion, the air transport, soil accumulation and the groundshine models of SENES were not modified, except for changes in I/O as required. Details of all subroutines are given below in Section E.1.3.

E.1.2 Review of SENES Code Structure

As noted by SENES (1985), "the probabilistic analysis process is inherently large and complex, hence a logical, step-by-step approach is required to make it tractable. The process is exceptionally well-suited to the application of a "top-down" computer programming approach. The top-down approach first involves identification of the overall system requirements, followed by the specification of large, conceptual structures consistent with these requirements, followed in turn by further development of conceptual substructures. The overlying conceptual structures always dictate the nature of lower level structures. The requirements and specifications are subsequently translated into identifiable tasks. Once the conceptual algorithms are developed in this logical, top-down manner, implementation is a fairly mechanical programming exercise".

The system model is composed of "control modules" and "simulation (component) modules". The latter are the mathematical models describing the physical system of interest. They are, in general, unique to each tailings site, although in some cases they can be very similar or the same.

E.1.3 Code Structure of this Study

The code structure used in this study is similar to that of SENES except that a different data structure was used. In general, there are three elements of the data management structure: management of input/output (I/O), the storage of parameter distribution information, and the storage of the rest of the program variables.

In BEAK (1986) and at the start of the project, a thorough review of the whole data management and code structure used by SENES, was undertaken. The attributes of a general program structure were discussed and defined by BEAK. In BEAK (1986), a new structure was proposed by a computer science specialist on our team. The basic ideas concerning this new data structure revolved around a completely dynamic design involving one main data stack accessed by local pointers. The scheme had some advantages and some disadvantages in Fortran, the language used in the code. This dynamic scheme was implemented in the BEAK (1986) code for the storing of the parameter distribution information due to the manner in which the parameter distribution data structure varies from one data set to another and from one parameter

in a given data set to another within the same data set. For example, some distributions require only two defining parameters, while others require three or four. This allows a flexible input/output structure because new variables to be treated as input can be added to the program input structure without changing other data components.

This dynamic scheme, however, was not used for the variables of the main program. Rather, a much simpler, static data design was used. In this static design, the data variables are of fixed sizes and most are classified and passed through common blocks. Generally all data variables are of fixed size. A few are of variable size where their size is program determined. Information flow between subroutines is passed via labelled common blocks, or through the subroutine call statements. Labelled common blocks were designed so that variables common to as few subroutines as possible are included in each common block. Common blocks are included in a subroutine only if necessary. This aids in error tracing.

Although the dynamic pointer oriented method would have resulted in a unrestricted data storage setup, it would have done so at the cost of a much more complex (and thus harder to follow) code and a slight increase in memory requirements. Normally, a dynamic design results in lowered memory requirements but its savings in memory is outweighed by the stack pointer system's overhead.

For this project, the above decisions were again assessed and the structure of BEAK (1986) retained. The structure allows the ease of modifying the existing code and the ease of incorporating whole subroutines or groups of subroutines into the existing code structure. It limits the scope of error diagnostics to areas modified in the code and the associated common block.

The input distribution data is read into the dynamic structure through an I/O subroutine, sampled from distributions obtained from SENES Phase II code and then sent to the various common blocks to be fed into the computational routines, by new subroutines programmed for the project. The sampling distribution added to UTAP in the earlier BEAK (1986) study, a correlated log normal distribution, was also retained in this code.

The random sampling for parameter values, control of the number of simulation passes, and preparation of summary statistics is executed by substructure RANSIM, similar to

SENES. The set of execution steps is defined in a subroutine called CONTRLS. The subroutine CONTRLS carries out essentially the same function as PAC in the SENES (II) code, but does not allocate parameter values. Due to the large set of new subroutines added for this study, a new CONTRLS Subroutine was written for this project. It controls the segregated logic of calculations from the tailings to the human receptor and the time progress of simulation for any one simulation. Information such as the concentration or dose calculated by the different subroutines are either summarized by the summary statistics and written directly to the storage files, or are passed to storage areas by the CONTRL module.

Summary statistics and detailed results of all simulations are stored on hard disk. These storage files are used as input data to graphic programs, written by team members to produce the output plots given in this report directly by the micro computer system. The plots are visually compared with numerical values in the storage files to ensure their veracity.

E.1.4 Description of Subroutines

The following subroutines are used in the version of UTAP called UTAP3.RAB to evaluate the environmental chemistry and dose from the Rabbit Lake tailings to two potential receptor groups. For each subroutine, its function is described and the major changes from the UTAP Phase III code (SENES, 1986) and the UTAP Demonstration code (BEAK, 1986) are pointed out.

1. RANSIM

- o main control module; calls ASSIGN
- o from BEAK (1986)

2. ASSIGN

- o assigns data from sampled input to common block variables
- o from BEAK (1986)
- o changed dimensions of several variables and added new ones

3. INITHYD

- o calculates individual flow rates through each tailings box
- o from BEAK (1986)
- o modified calculation of water balance through each box and through the whole tailings: infiltration and flow from North Ridge are dispersed into outflow in the north, south and easterly directions
- o perform a flow balance on total inflow and total outflow and for each box and for complete tailings pile

4. INTCHEM

- o calculates initial chemical conditions
- o from BEAK (1986)
- o modified to give capability of putting coarse or fine solid concentrations for each box

5. COVERS

- o controls affected parameters for management scenarios
- o new subroutine

6. FLOW

- o called by INITHYD
- o calculates:
 - flow out of each box for mass balance purposes
 - distributes flow out of boxes into appropriate groundwater paths
 - input flows for each lake
- o new subroutine

7. SOURCE

- o calculates solid and liquid concentrations for each box in tailings
- o from BEAK (1986)

- o changes:
 - added Mg and NH₃
 - removed As and Ni
 - changed MSBAL1 and MSBAL2 to perform calculations on total flux in and out (MBALIN; MBALOT)

8. LDWIND

- o reads Star data deck for wind rose data
- o from SENES (1986) Phase III - Input 2 subroutine
- o calculates midpoints of and ring areas; reads and opens specified input file (in input data deck) for wind rose data

9. PAC

- o control module for stepping through time
- o from BEAK (1986)
- o added calls to new subroutines and changed common blocks

10. WIND

- o calculates wind velocity and directions from Star data
- o from SENES Phase III
- o modified so that, if more than one year of wind data is input, the program will randomly select one of these years for each time step of each iteration

11. LDATM

- o transforms units from source to atmosphere subroutine
- o from BEAK (1986)
- o handles mass ratio of Th-232 (source) to Th-230 (atmosphere)

12. EROS

- o calculates bulk tailings erosion due to precipitation

- o SENES Phase III
- o modified so that eroded depth is calculated for each time step

13. DUST

- o calculates atmospheric emission rates from each radionuclide as a result of wind
- o from BEAK (1986)
- o time of full vegetation is input and is further attached by COVERS subroutine

14. SILTATION

- o calculates increase in silt content from erosion of larger particles and the subsequent volume changes
- o from BEAK (1986)
- o also calculated removal of top box due to physical erosion in EROS subroutine

15. RADON

- o calculates radon flux through the soil to the atmosphere
- o from BEAK (1986)

16. LOAD SS

- o transforms bulk mass eroded from EROS into concentrations to be fed into lake
- o models deposition of load into a local pond and the transport of the residue to the lake
- o new subroutine

17. SOIL

- o calculates concentrations in soils
- o from SENES Phase III
- o modified:
 - CAIR into radionuclide order used in soil.f
 - input three layers
 - to perform calculations for each receptor within the subroutine

18. GSHINE

- o calculates groundshine doses for U, Th-232, Pb and Ra and total dose
- o from SENES Phase III

19. LOAD GW

- o transforms concentration units from source to groundwater
- o from BEAK (1986)
- o contributions from each box are weighted on a flow basis for each pathway
- o fraction of groundwater contributing to surface water removed

20. GD H201 - GDH207

- o seven subroutines
- o each calculates concentrations emitting from one groundwater pathway
- o from SENES Phase III
- o sequentially performs calculations for each pathway within subroutine

21. LOAD LK

- o aggregates loading from groundwater paths to Parks Lake and Hidden Bay, specifically loading from four groundwater paths 1, 5, 6 and 7 to Parks Lake and three groundwater paths 2, 3 and 4 to Hidden Bay
- o changed from BEAK (1986)
- o loading for C_T , A_{lk} and radionuclides calculated on a flow-proportional base

22. LAKE

- o calculates concentrations in lake
- o changed from BEAK (1986)
- o added:
 - desorption from increased sediment loading due to tailings erosion
 - loading from groundwater pathways to Parks Lake and Hidden Bay

23. FC UNIT

- o transforms lake concentrations into appropriate units for vegetation and human uptake
- o from BEAK (1986)
- o also converts vector order of radionuclide in SHINED and CSOK back to BEAK vector order (i.e., U-238, Th-230, Ra, Pb, Po)

24. AQBIOTA

- o calculates intake by aquatic biota
- o remains unchanged from BEAK (1986) except for performing calculations for each receptor
- o calculations for Ni and arsenic removed

25. VEGDEP

- o calculates vegetation intake from air and soil concentrations
- o BEAK (1986)
- o calculates concentrations for each receptor

26. DOSEIN

- o performs dose calculations
- o BEAK (1986)
- o calculates doses for each receptor

27. TIMOUT

- o stores parameters for plotting and statistics output
- o BEAK (1986)
- o changed data stored for parameters to retest various new plots

E.2 Walk Through of Model Calculations as Quality Assurance Check

Quality assurance aspects include checks on coding, comparison of model calculations with test examples and inspection of model calculations. This appendix presents a walk-through of the concentrations calculated in the various environmental media using a time step of 25 years. The media described are:

- o the seven boxes of the tailings pile;
- o the toes of the north and south dams;
- o the three lakes (Parks, Hidden Bay, Wollaston Lake);
- o air concentrations at the site of the two potential receptors; and
- o soil concentrations in the garden of the Wollaston Lake potential receptors.

E.2.1 Tailings Pile

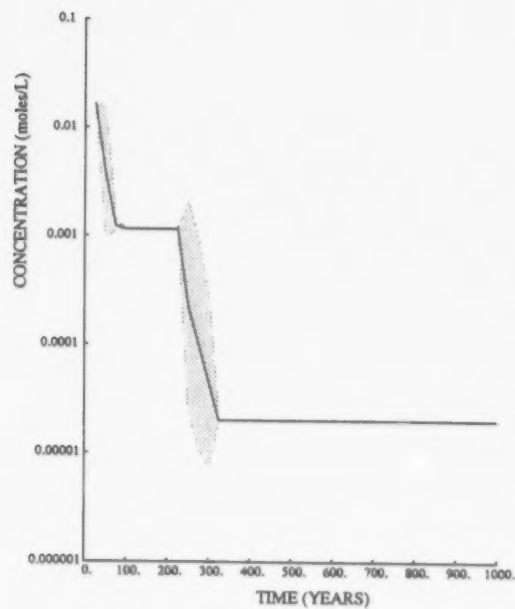
The porewater concentrations of calcium (a), sulphate (b), carbonate (c), pH (d), uranium (e), thorium-232 (f), Ra-226 (g), and Pb-210 (h) are given respectively for the seven boxes in the following figures:

- o Figure E.2.1: Box 1 (Unsaturated Zone, Coarse)
- o Figure E.2.2: Box 2 (Unsaturated Zone, Coarse)
- o Figure E.2.3: Box 3 (Saturated Zone, Fine)
- o Figure E.2.4: Box 4 (Saturated Zone, Fine)
- o Figure E.2.5: Box 5 (Saturated Zone, Fine)
- o Figure E.2.6: Box 6 (Unsaturated Zone, Coarse)
- o Figure E.2.7: Box 7 (Saturated Zone, Coarse)

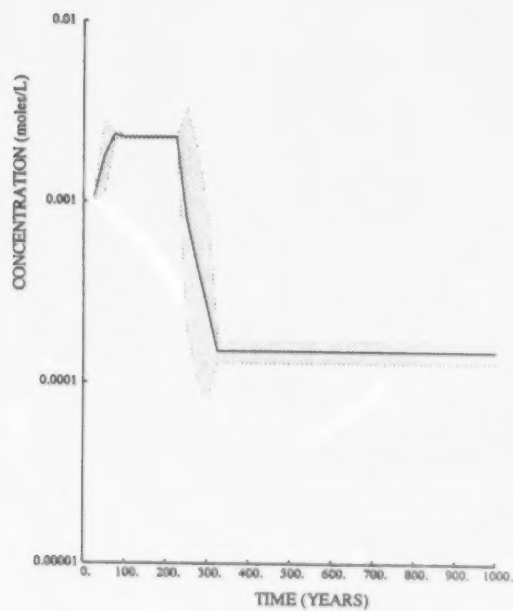
The top box for most of the tailings, Box 1, shows a pattern in which gypsum washes out at approximately 100 years causing a new plateau in calcium and sulphate concentrations. The decrease in sulphate in the first time step is caused by the washout of magnesium and the associated magnesium sulphate complexes. Following this 100-year period, the carbonate phase concentrations change, at approximately 400 years, resulting in new values for calcium and carbonate. These new plateau values are those dictated by solution mass balance from rainfall and the partial pressure of carbon dioxide

FIGURE E.2.1 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 1
GEOMETRIC MEAN OF 5 TRIALS

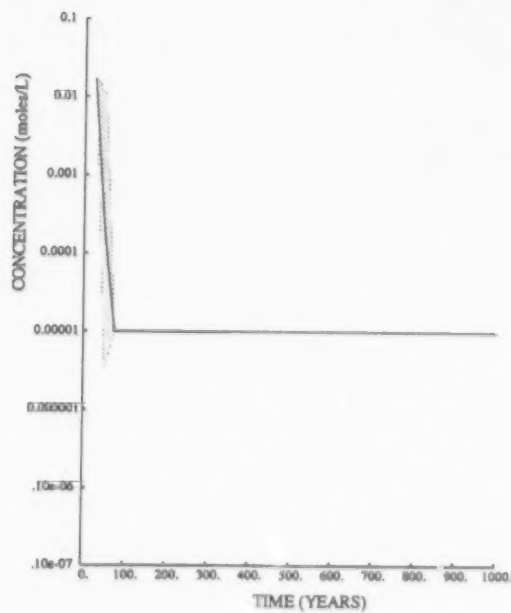
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

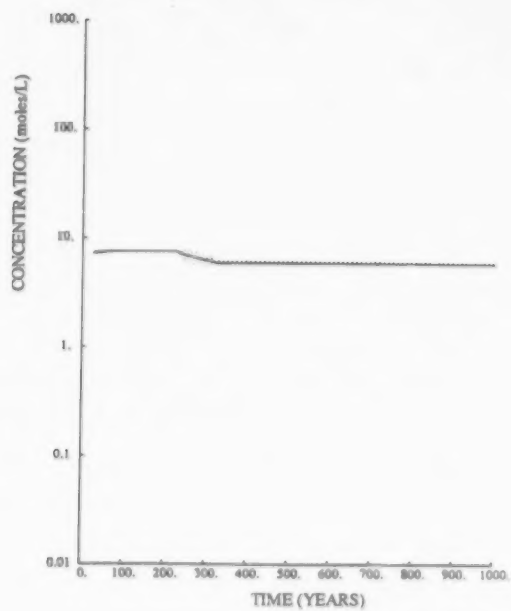
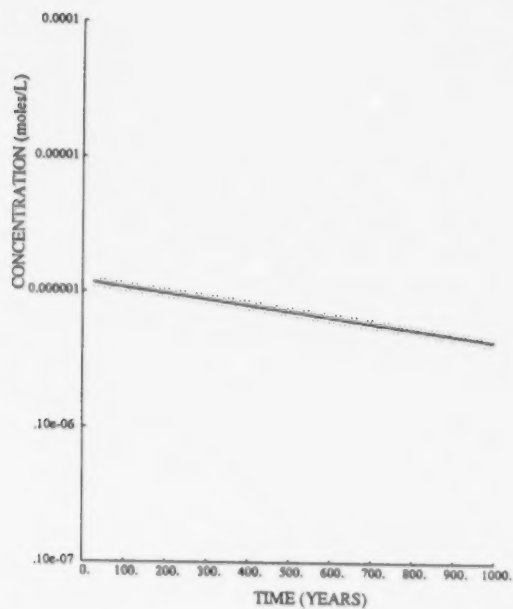
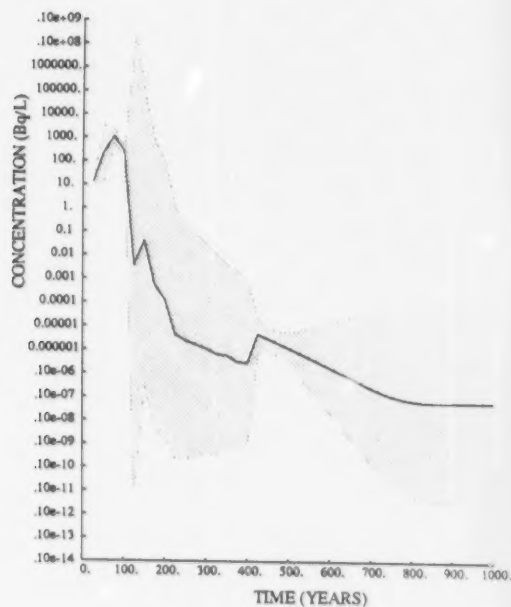


FIGURE E.2.1 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 1
GEOMETRIC MEAN OF 5 TRIALS

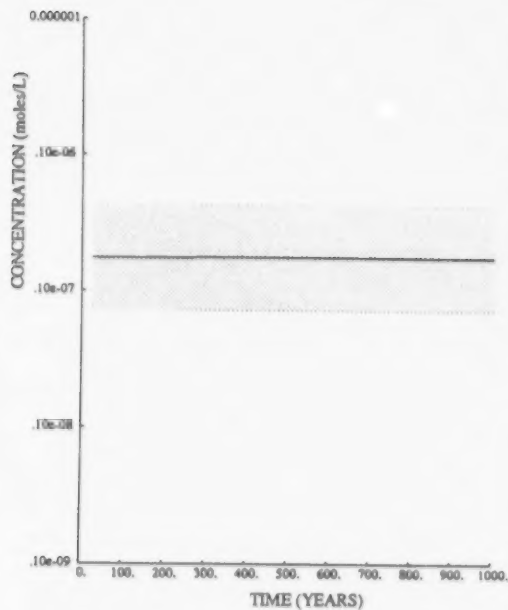
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

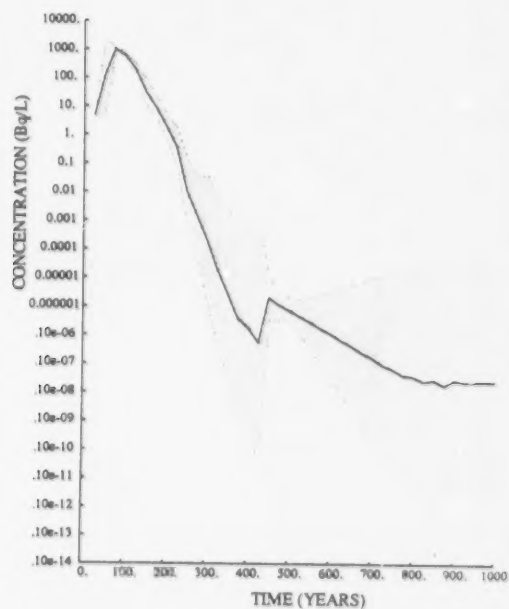
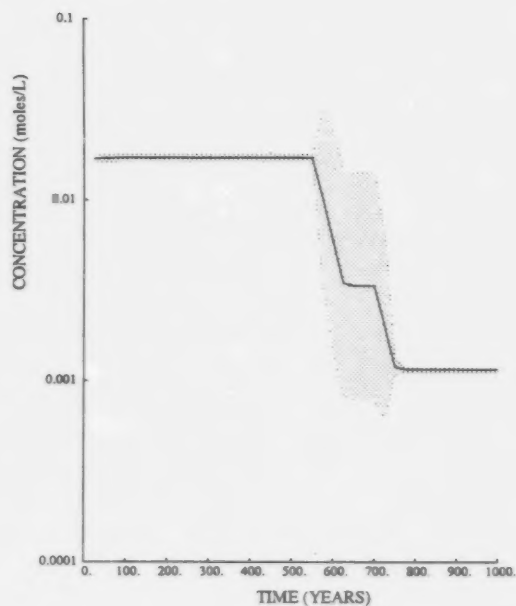
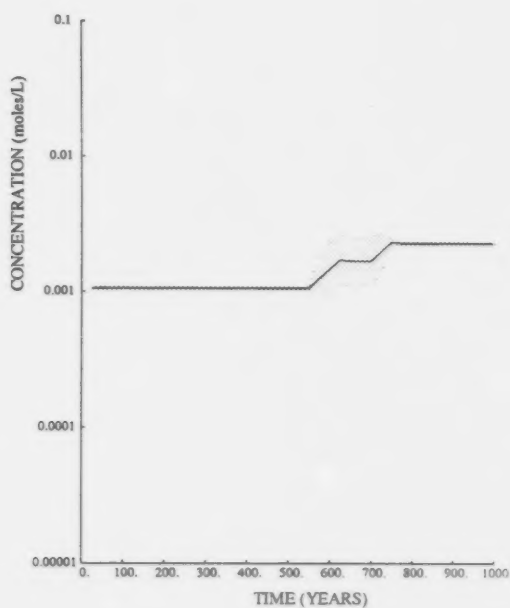


FIGURE E.2.2 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 2
GEOMETRIC MEAN OF 5 TRIALS

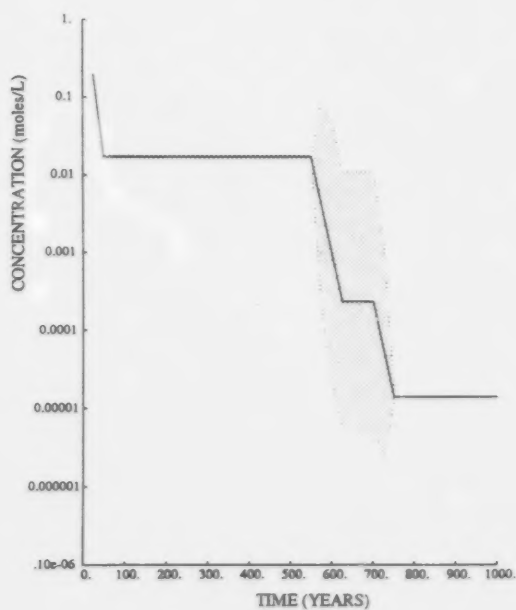
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

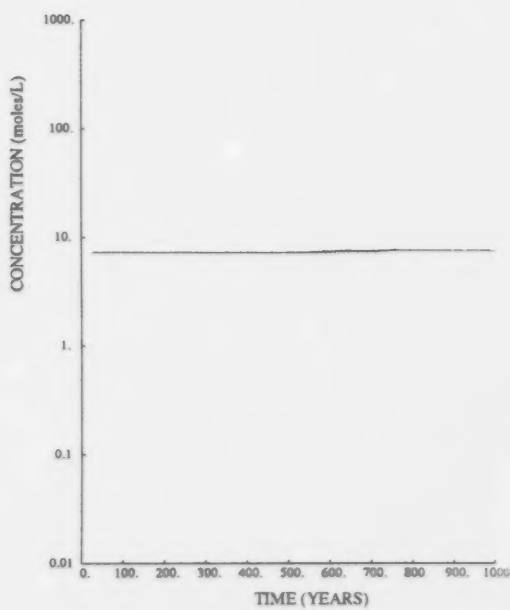
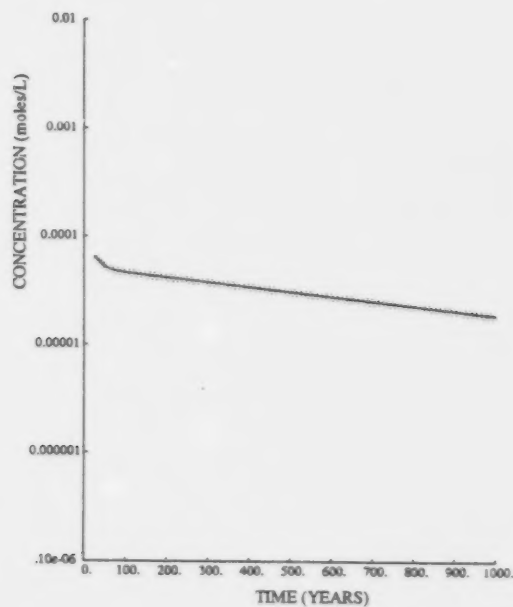
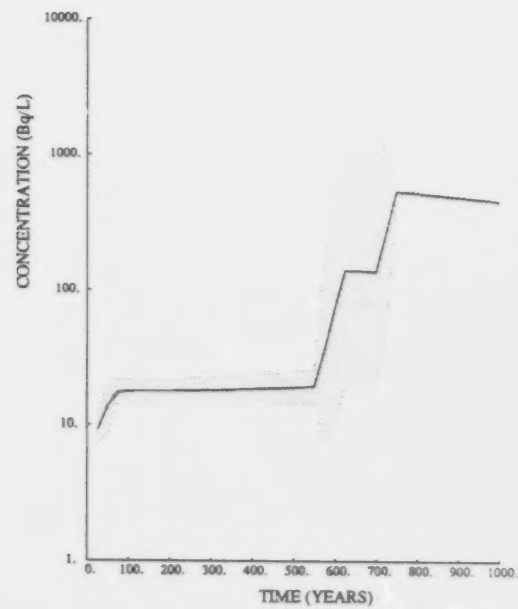


FIGURE E.2.2 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 2
GEOMETRIC MEAN OF 5 TRIALS

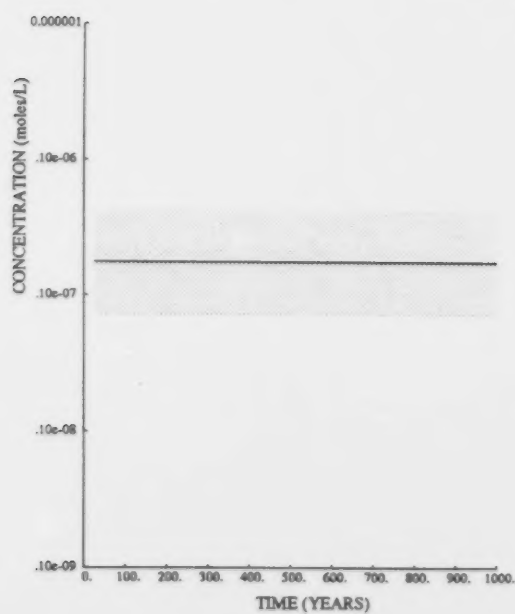
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

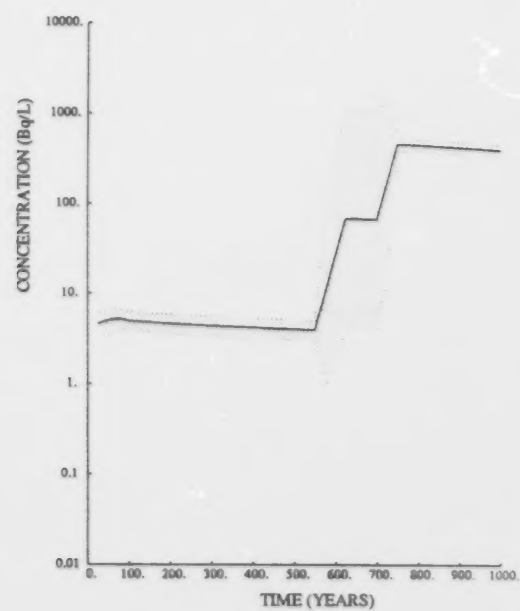


FIGURE E.2.3 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

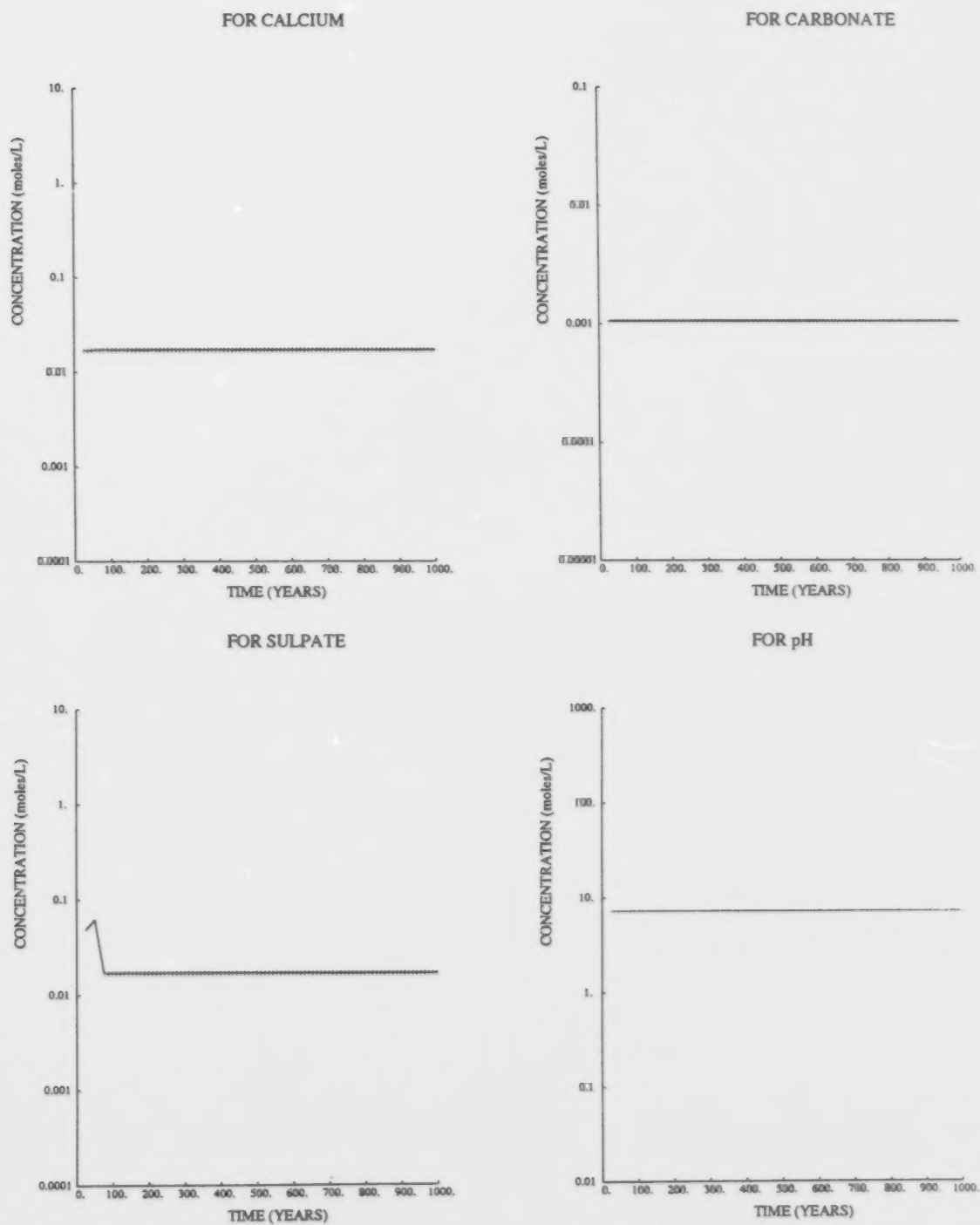
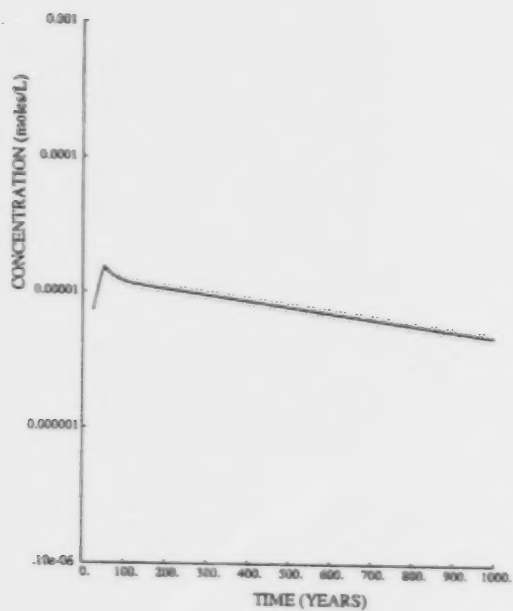
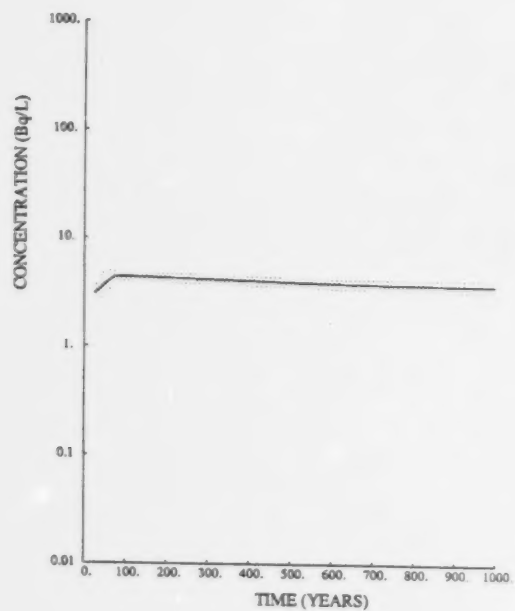


FIGURE E.2.3 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

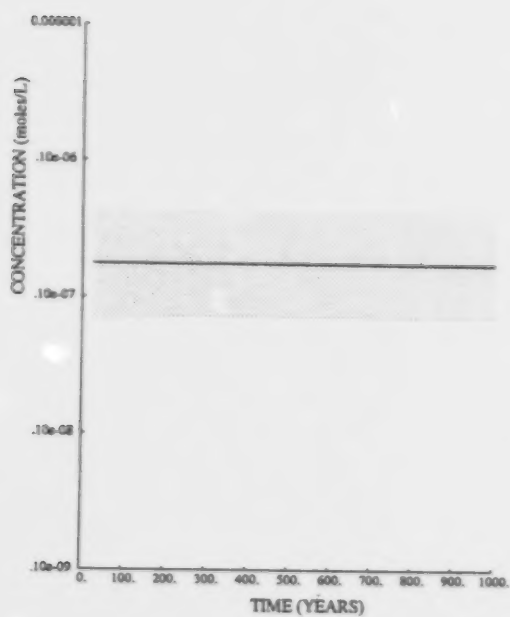
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

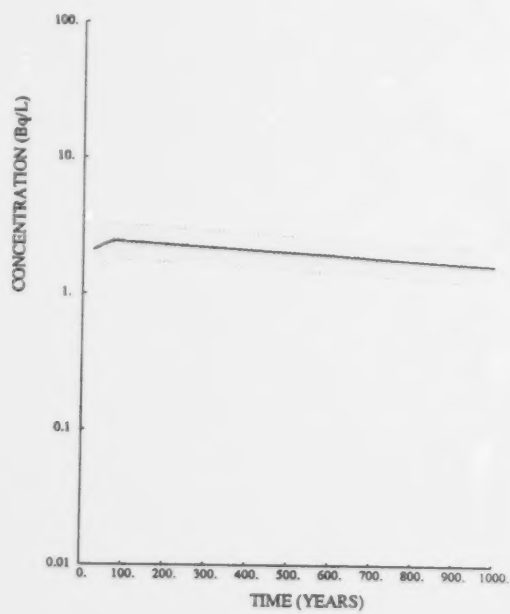
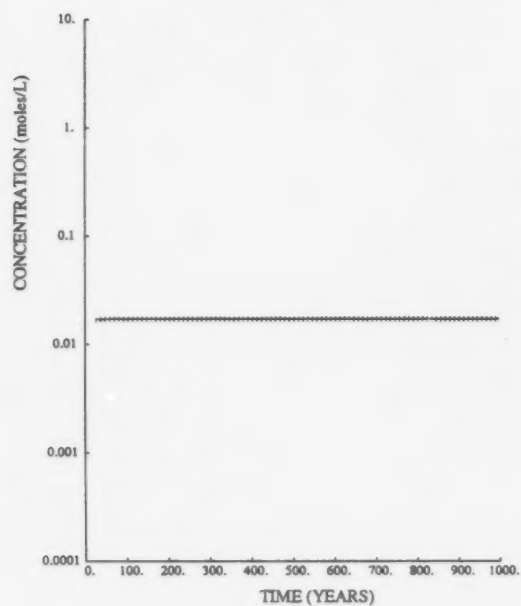
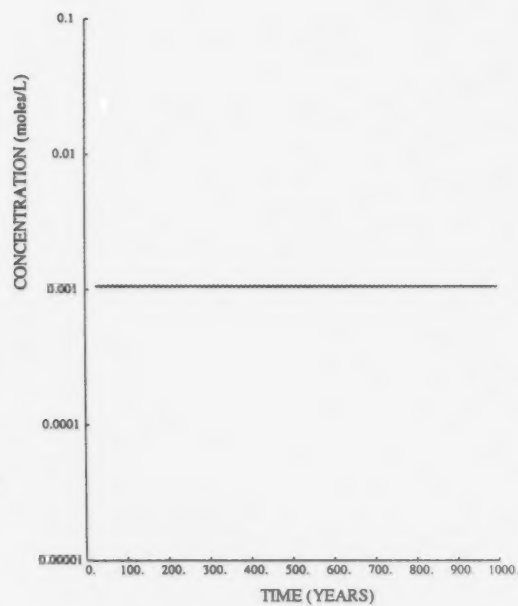


FIGURE E.2.4 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 4
GEOMETRIC MEAN OF 5 TRIALS

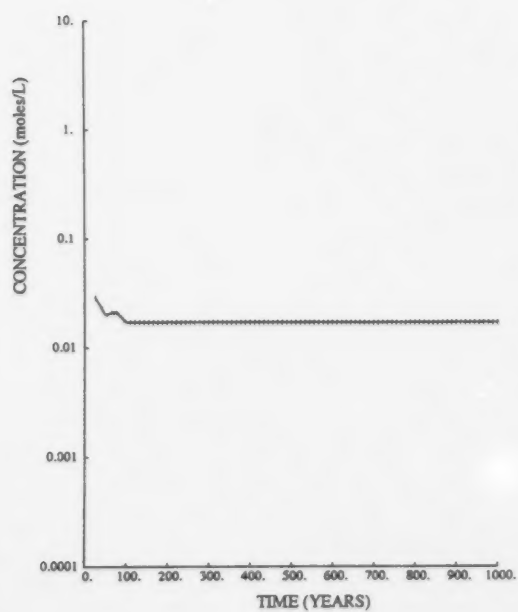
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

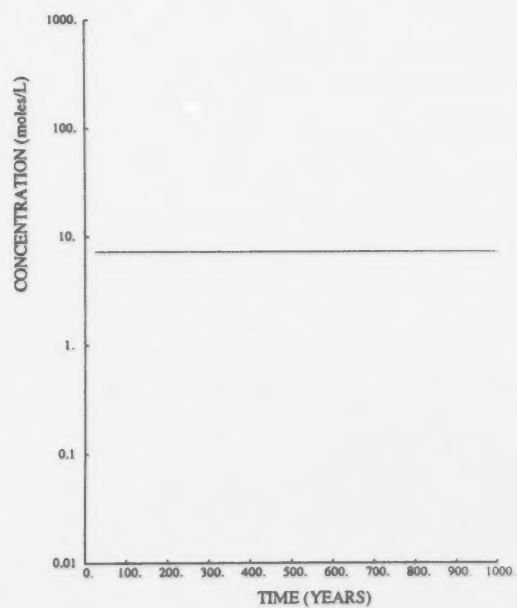
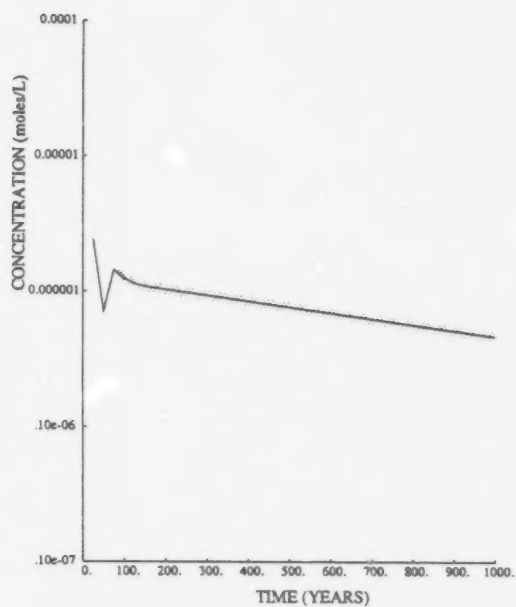
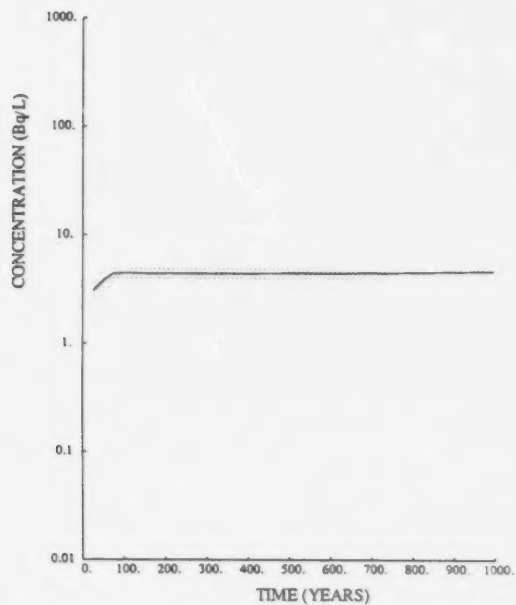


FIGURE E.2.4 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 4
GEOMETRIC MEAN OF 5 TRIALS

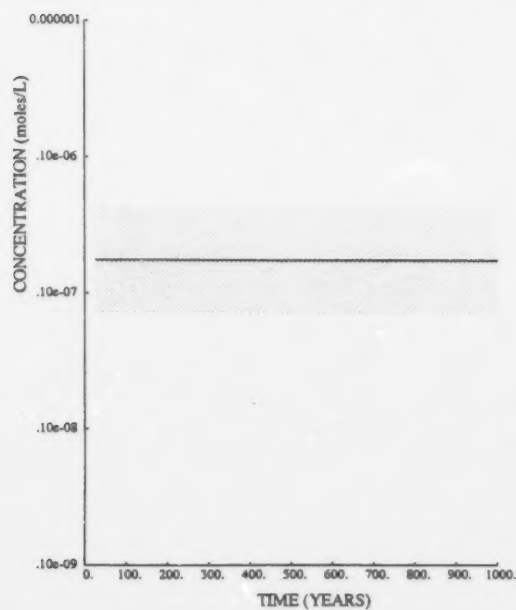
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

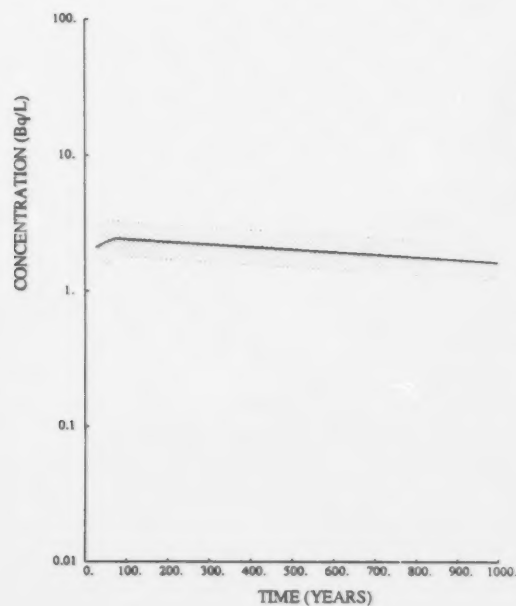
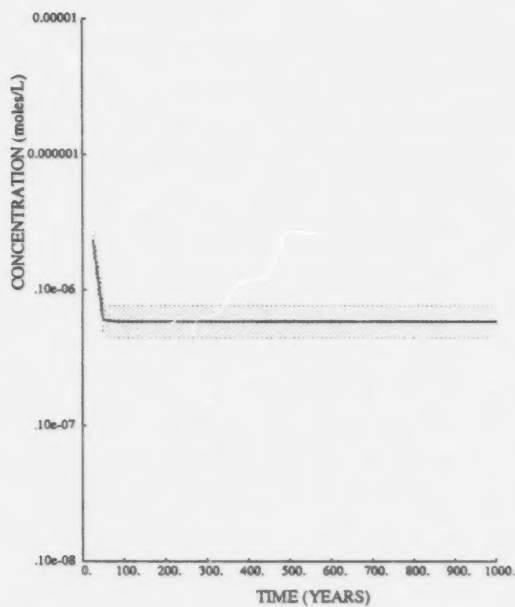
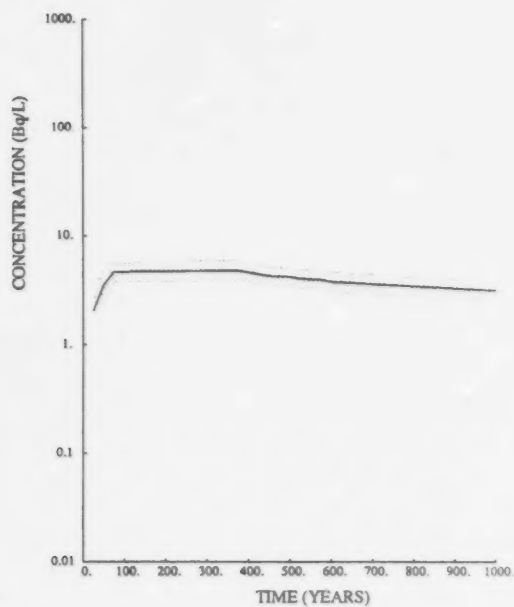


FIGURE E.2.5 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 5
GEOMETRIC MEAN OF 5 TRIALS

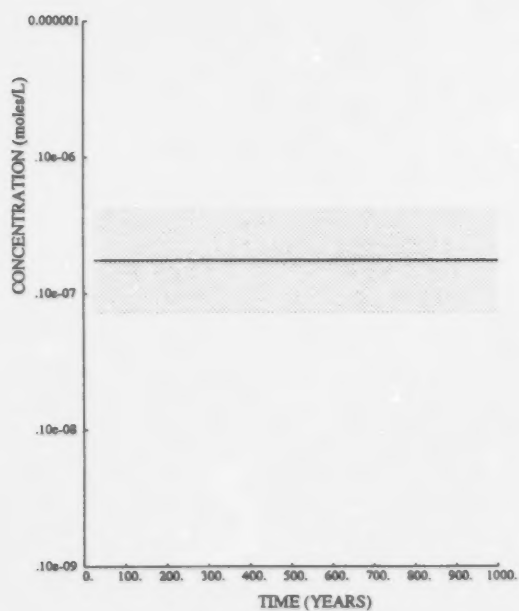
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

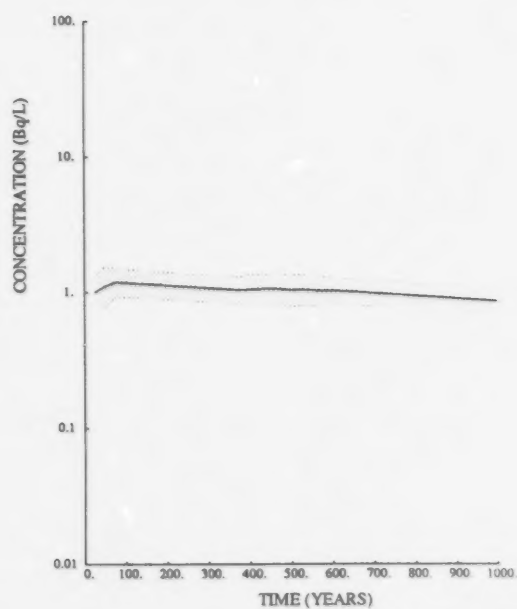
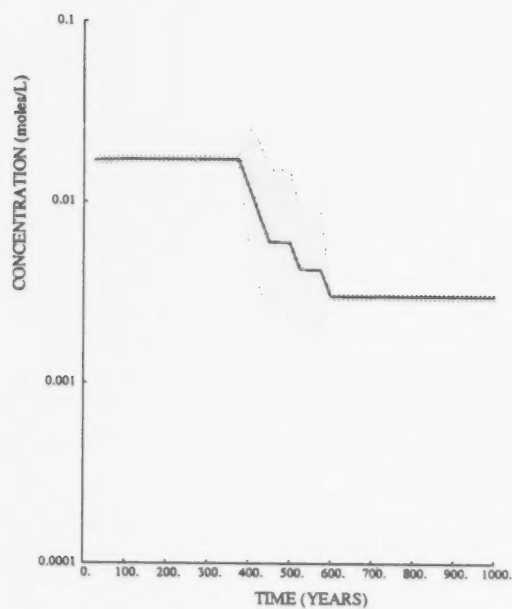
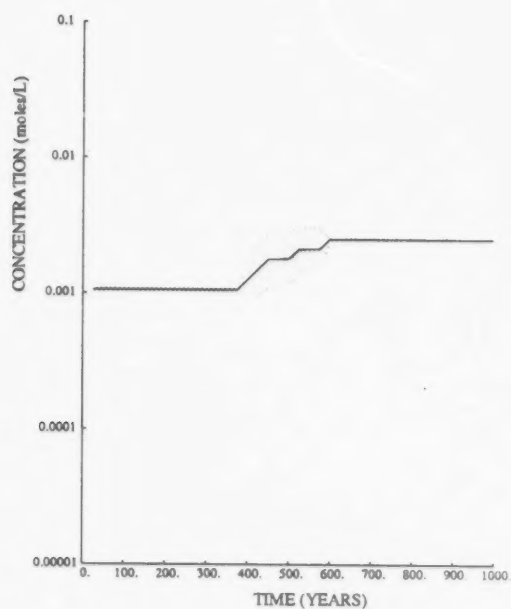


FIGURE E.2.5 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 5
GEOMETRIC MEAN OF 5 TRIALS

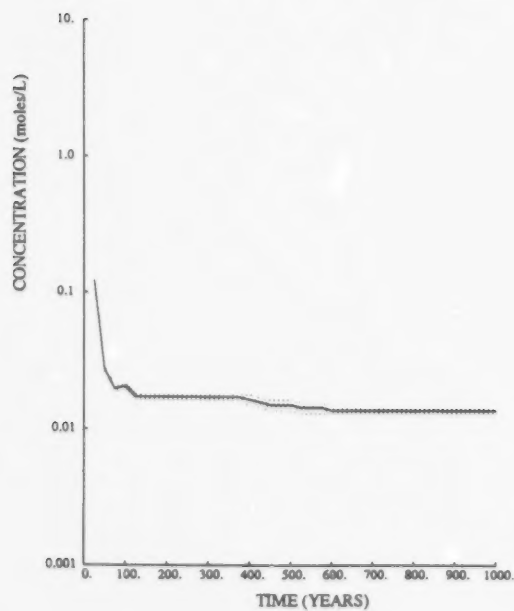
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

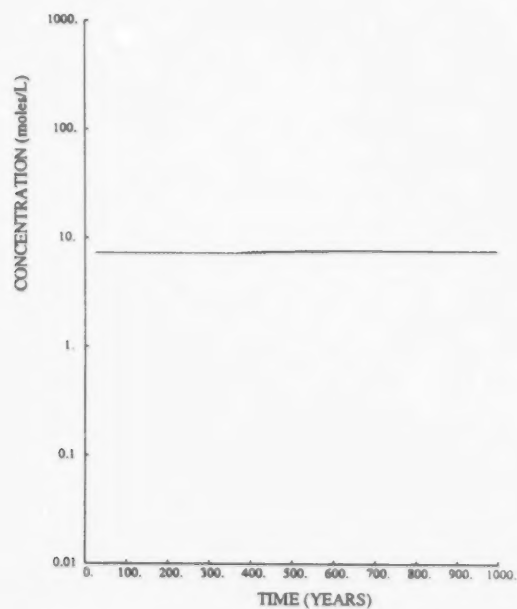


FIGURE E.2.6 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 6
GEOMETRIC MEAN OF 5 TRIALS

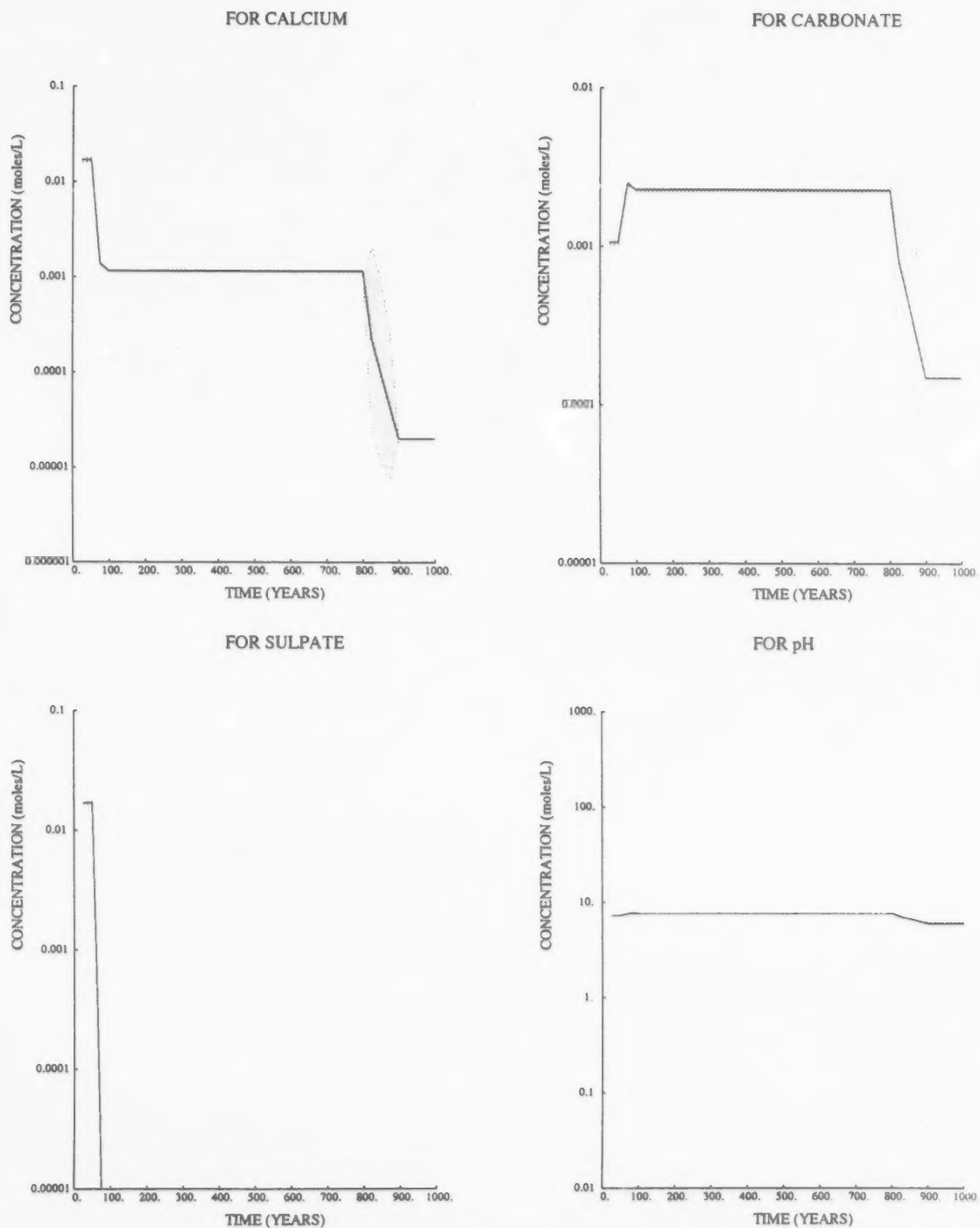
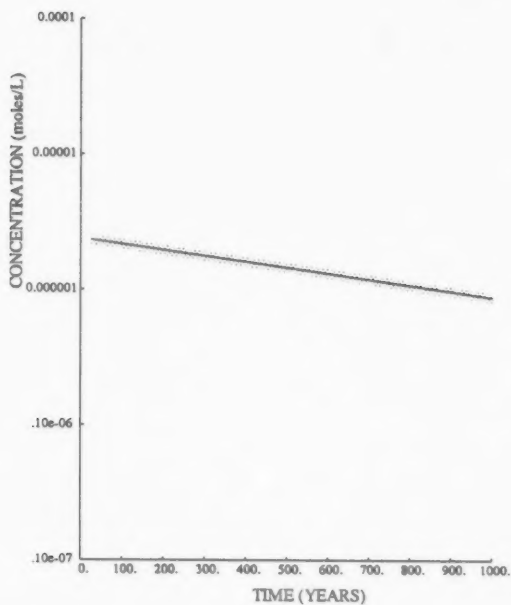
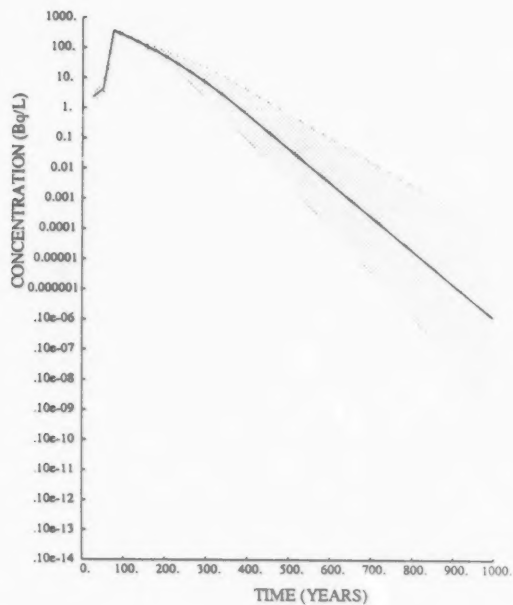


FIGURE E.2.6 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 6
GEOMETRIC MEAN OF 5 TRIALS

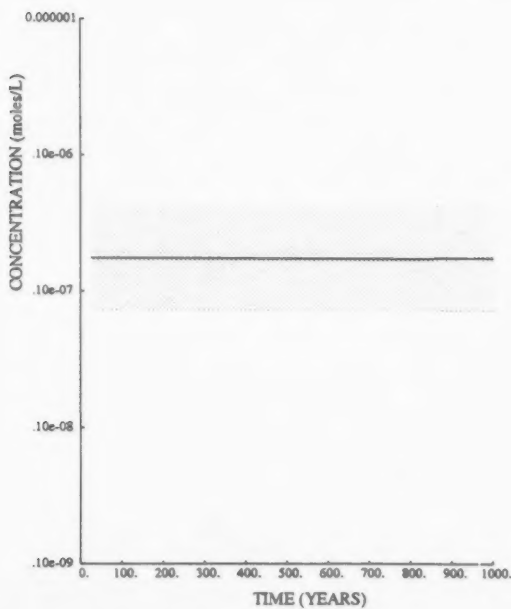
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

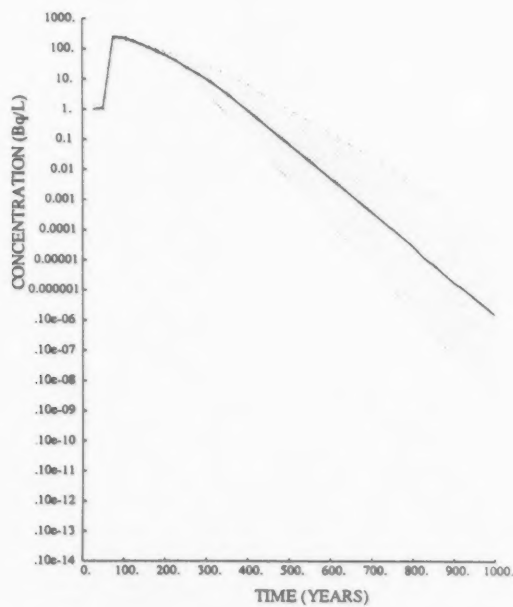


FIGURE E.2.7 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

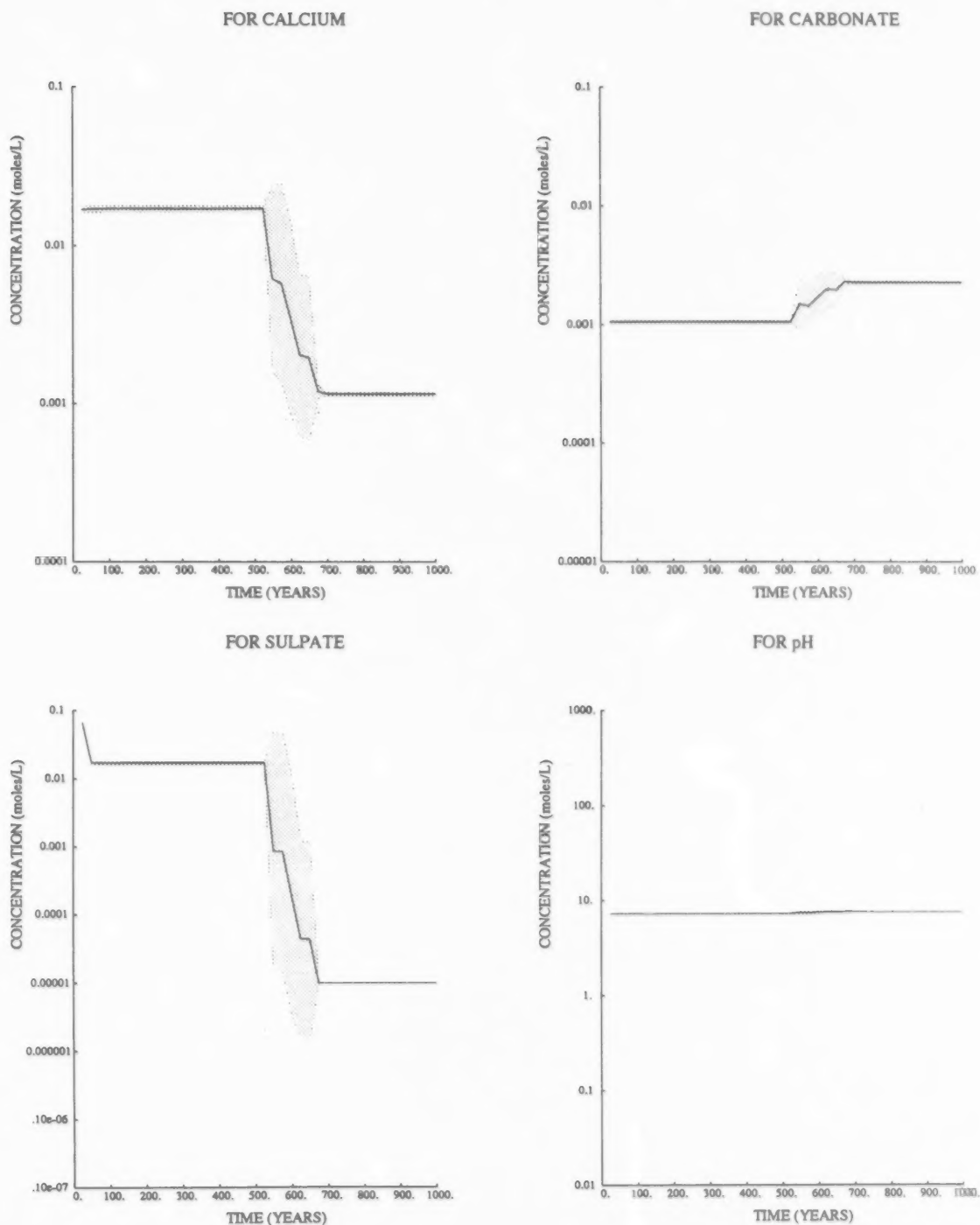
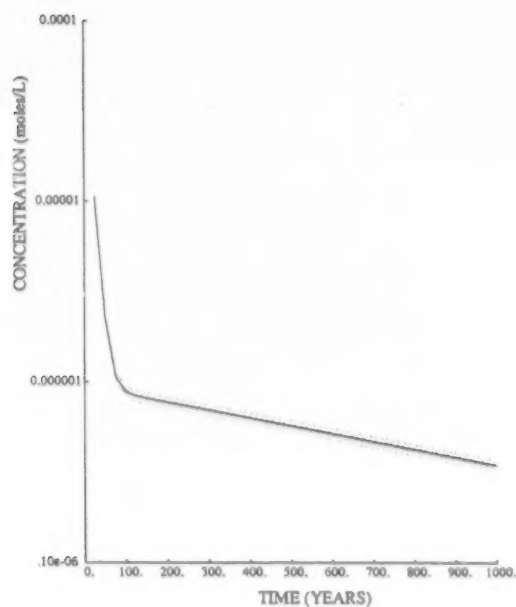
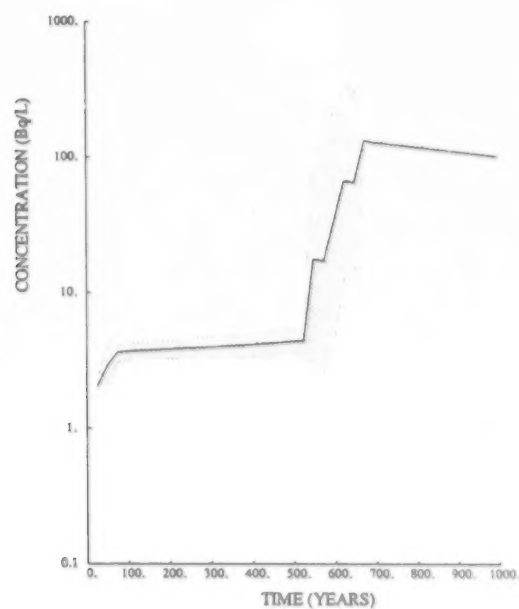


FIGURE E.2.7 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

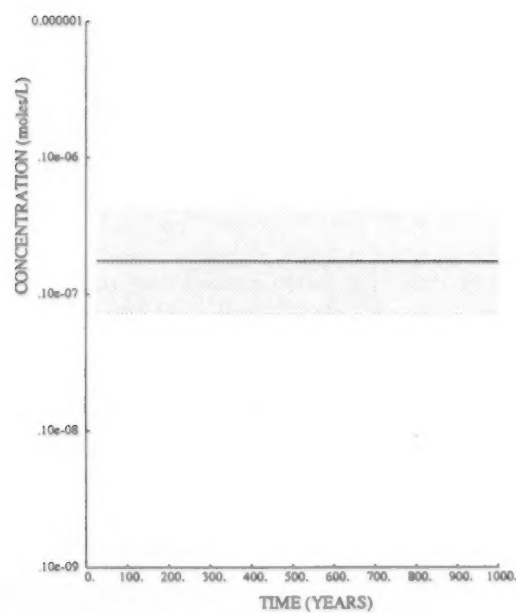
FOR U-238



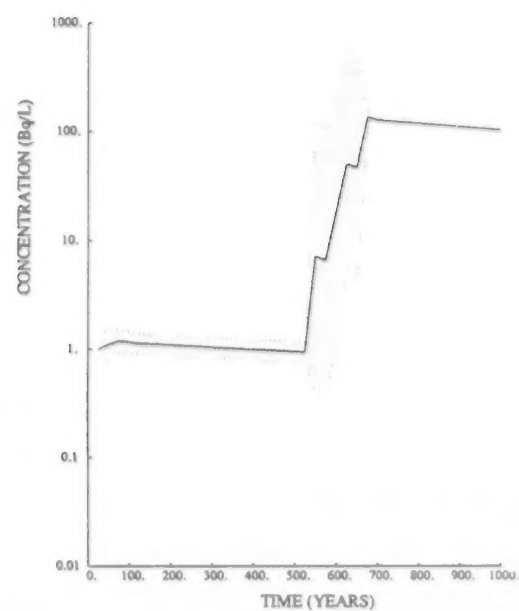
FOR Ra-226



FOR Th-232



FOR Pb-210



in the gas-filled voids of the tailings. Associated with these changes in the secondary minerals are small changes in pH.

The model assumes a constant $p\text{CO}_2$ in the unsaturated zone of the tailings which is a probabilistic variable with a specified frequency distribution. This is inadequate for conditions where all carbonate minerals have been depleted; a mass balance model for $p\text{CO}_2$ in the gas phase needs to be developed to give better predictive capability to the model.

The graphs for uranium-238 show a small decrease with time for the pore water of Box 1 and a relatively invariant Th-232 concentration. The depletion of U-238 reflects oxidation of residual minerals, while the Th-232 pattern is governed by the relatively constant pH through its effect upon the solubility of Th-232 in the pore water.

The activity of Ra-226 and Pb-210 show a much more dramatic change with time. The pulse of Ra-226 and Pb-210 shortly after 100 years are associated with the complete dissolution of secondary precipitates which control Ra-226 and Pb-210 through the coprecipitation process. After solid phase dissolution, the activity of both isotopes decreases due to the effects of washout in the mixing cell model. The residual Ra-226 in pore water is supported by ingrowth and dissolution of Ra-226 from Th-230 in the thorium hydroxide solid phase. Pb-210 is supported by ingrowth from Ra-226.

Concentrations in Box 3 show a nearly time invariant pattern for all substances. Both Ra-226 and Pb-210 show a small increase in the solid phase after 100 years due to the washout of Ra-226 and daughters from the top box (Box 1) at this time. Similar patterns are predicted for Box 4.

Similar patterns are predicted for all substances in Box 5, the box underlying the frozen zone of the tailings to those in Boxes 3 and 4, except for a small variation in the porewater concentrations of calcium due to a shift in the relative importance of gypsum and carbonate in controlling calcium concentrations. A small change in pH results. The effect upon radionuclide concentrations is, however, negligible. The change in porewater radium activity is caused more by the washout of Ra-226 from the top boxes.

Similar patterns are calculated in Box 6 as in Box 1. The effect of calcite is prolonged for a longer period of time due to the larger mass (depth of the box) compared to that of Box 1.

A slightly different pattern is predicted for Box 7 (Figure E.2.7). Gypsum is maintained until approximately 500 years when it is completely depleted; the resultant concentrations of calcium and sulphate decrease effectively to become a blend of rainfall inputs and groundwater inputs from the North Ridge. This results in a concurrent release of Ra-226 and Pb-210 due to washout of secondary precipitates containing these radionuclides.

Comparison between Boxes 6 and 7 shows that there is a small increase at 100 years in Ra-226 and Pb-210 activity in Box 7 (the box below Box 6) when these radioisotopes washout from Box 6. Both boxes are calculated to have a similar increase in porewater concentration of Ra-226 and daughters when the controlling coprecipitating phases washout, except for the different moisture contents of the two boxes and the timing of washout.

Solid phase concentrations for Boxes 1 to 7, given in Figures E.2.8 (a to d), reflect these porewater concentrations. The wide confidence band for gypsum at the time of its depletion (Box 7; Figure E.2.8a) reflects the assumption of a log-normal variate which is, in fact, constrained to the initial value.

E.2.2 Toe of Dam

The activity of radionuclides in the toe of the north and south dams are given in Figures E.2.9 (Toe of South Dam) and E.2.10 (Toe of North Dam). These activities essentially reflect the blended concentrations of porewater in the tailings and the effects of adsorption and associated radioactive decay.

The concentrations of uranium, radium-226, calcium and sulphate agree reasonably well with the presently observed concentrations in the toe of the dam (the circle at time 0). The calculated concentrations for Th-230 increase by an order of magnitude above the observed concentration and those of Pb-210 by one-half an order of magnitude. For uranium in the north dam, the calculated activity is an order of magnitude lower than

FIGURE E.2.8a CONCENTRATION vs. TIME
FOR GYPSUM
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

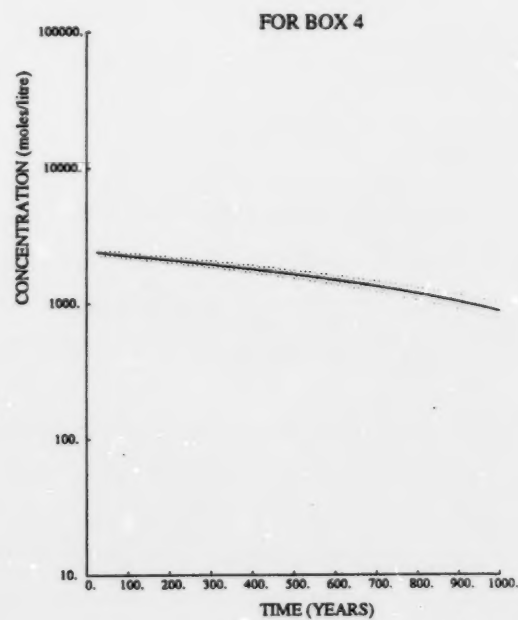
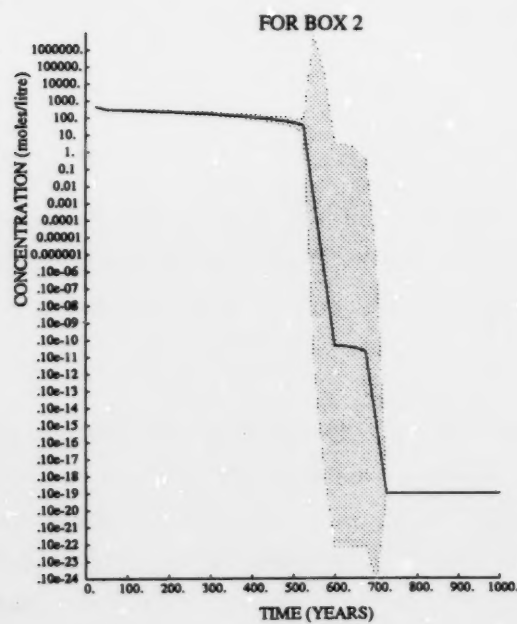
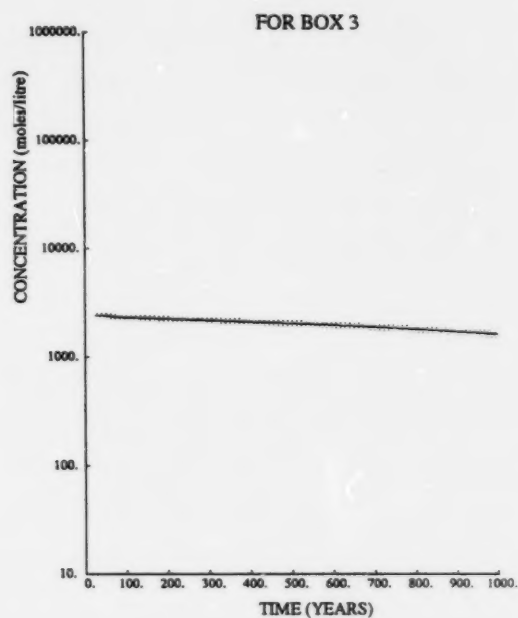
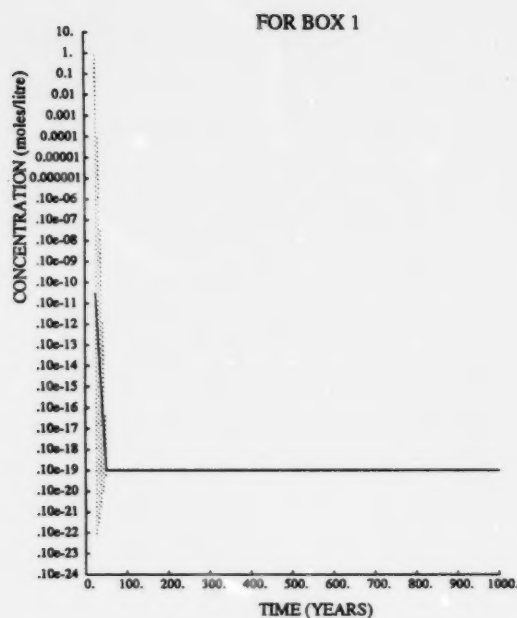


FIGURE E.2.8a CONCENTRATION vs. TIME
FOR GYPSUM
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

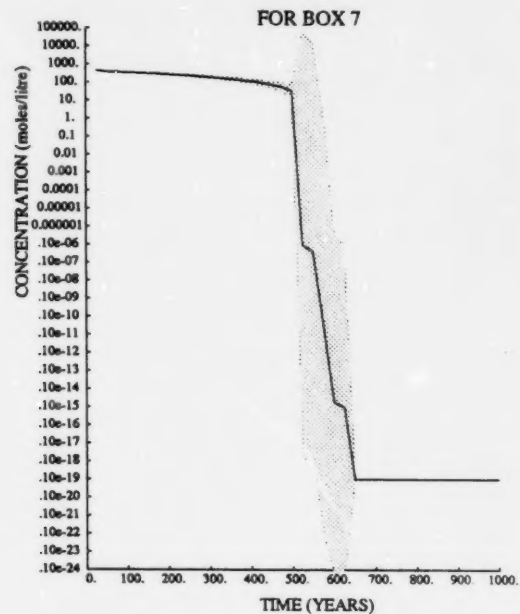
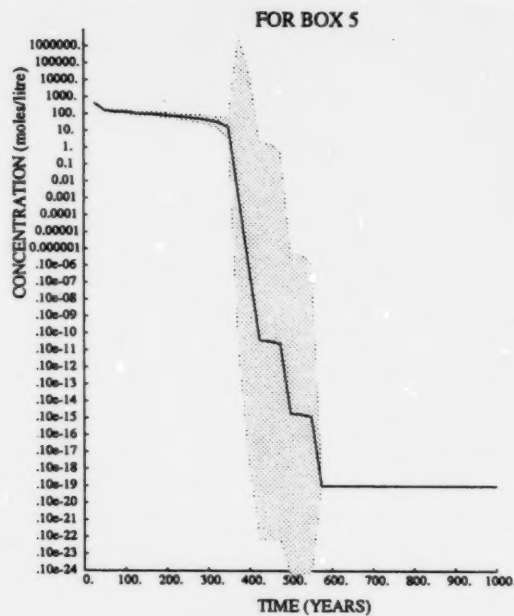


FIGURE E.2.8b CONCENTRATION vs. TIME
FOR CALCITE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

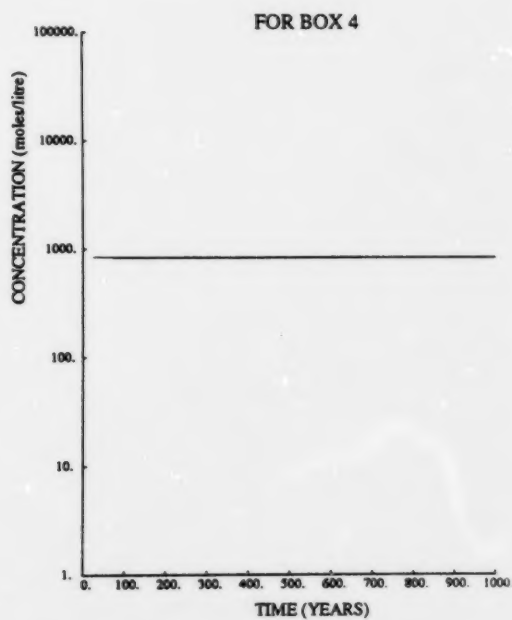
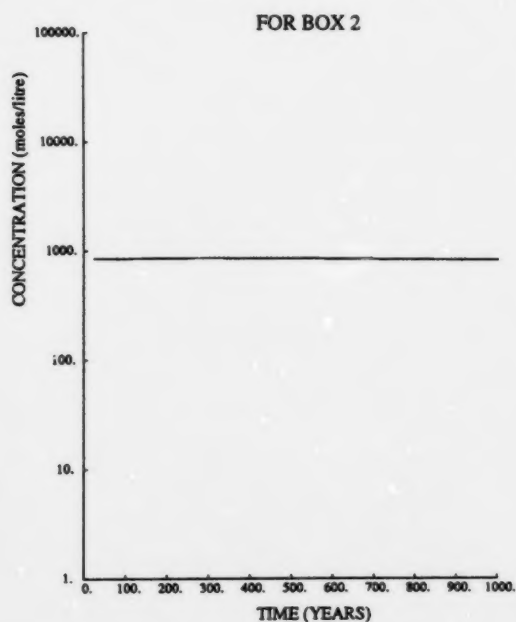
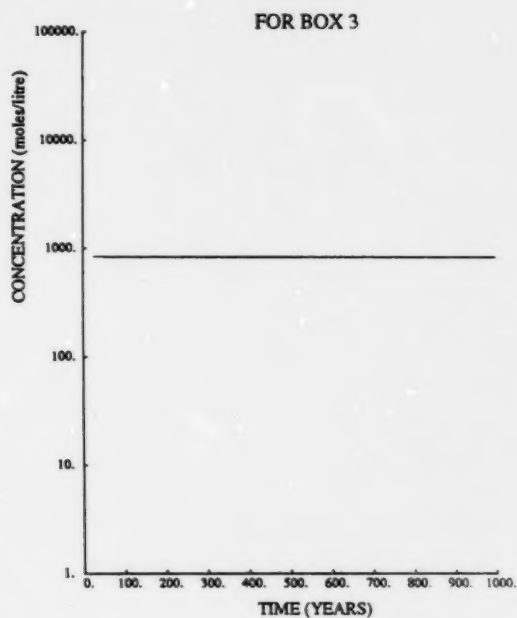
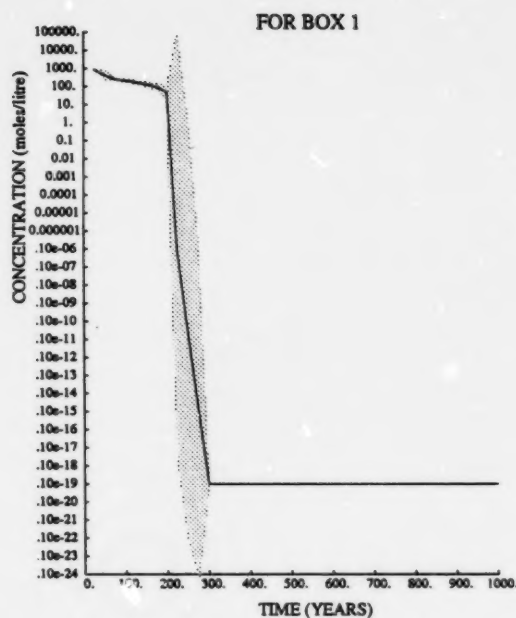


FIGURE E.2.8b CONCENTRATION vs. TIME
FOR CALCITE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

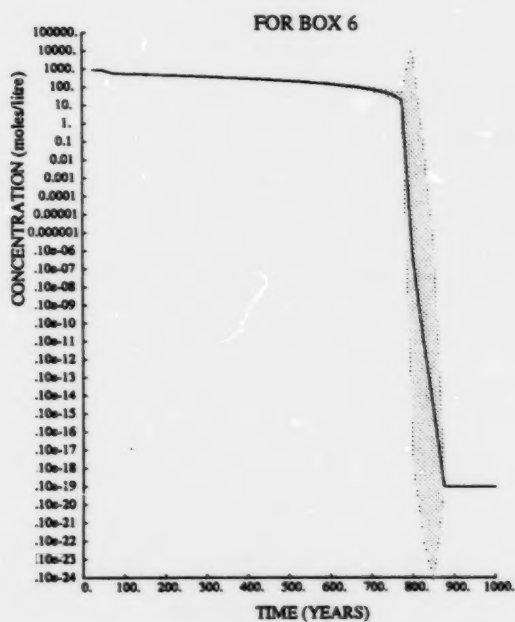
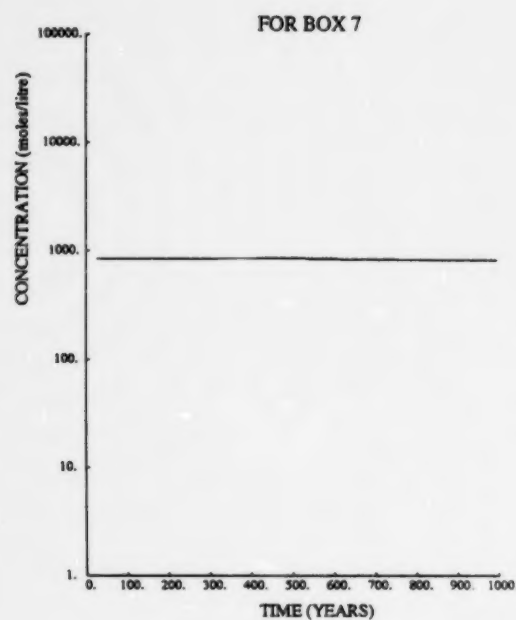
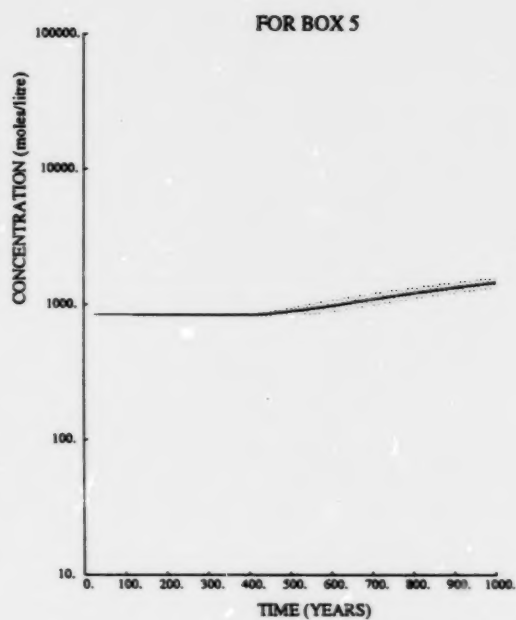


FIGURE E.2.8c CONCENTRATION vs. TIME
FOR BaSO_4
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

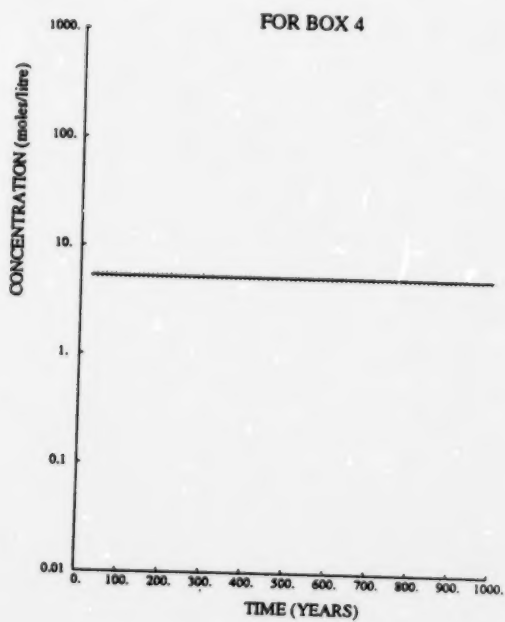
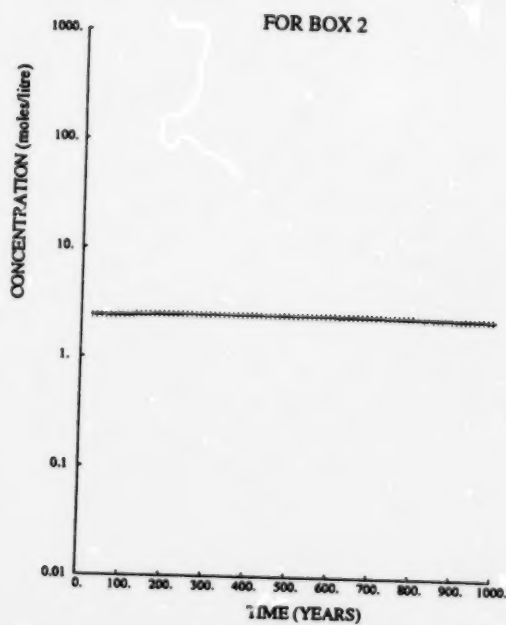
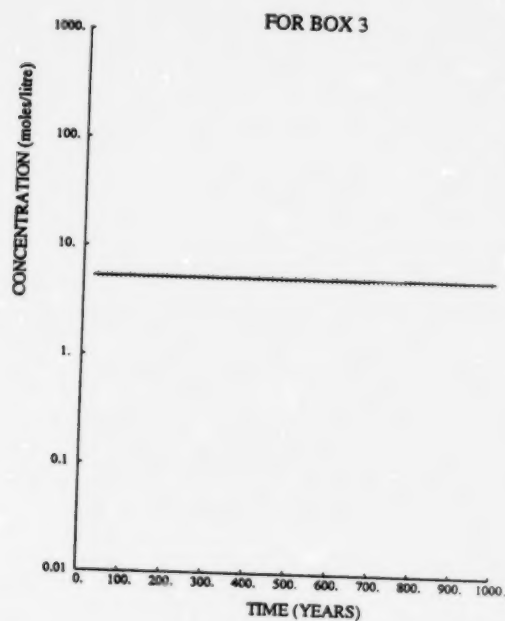
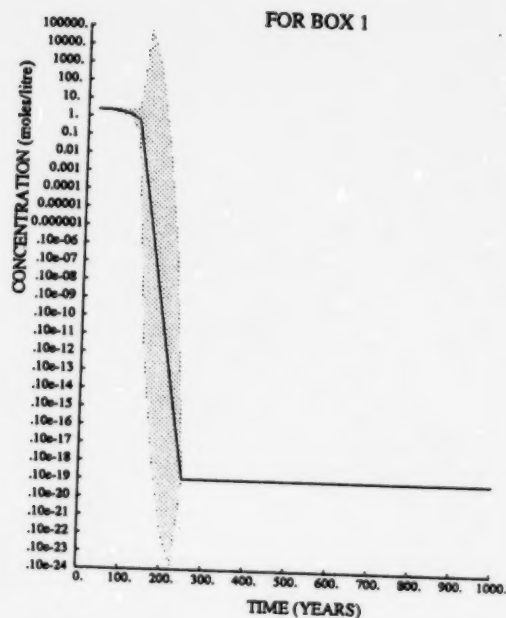


FIGURE E.2.8c CONCENTRATION vs. TIME
 FOR BaSO_4
 FOR SCENARIO 1
 GEOMETRIC MEAN OF 5 TRIALS

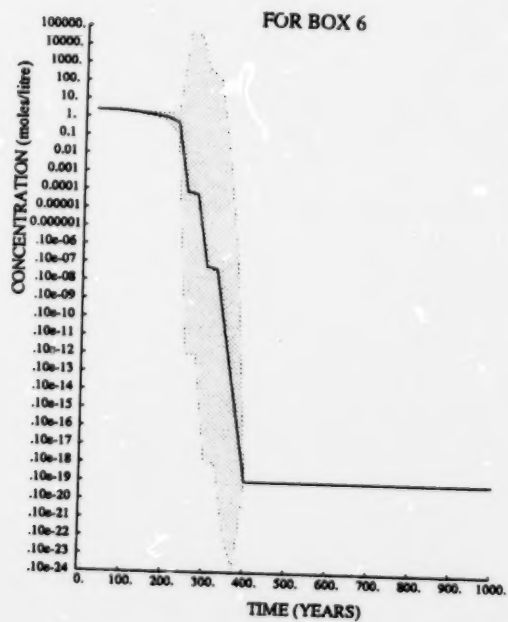
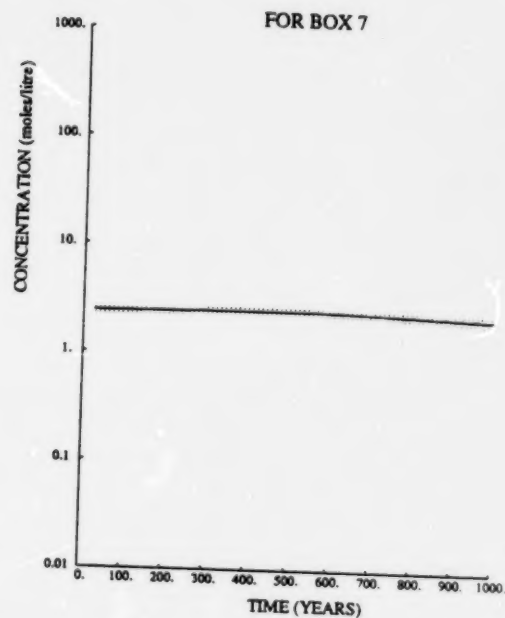
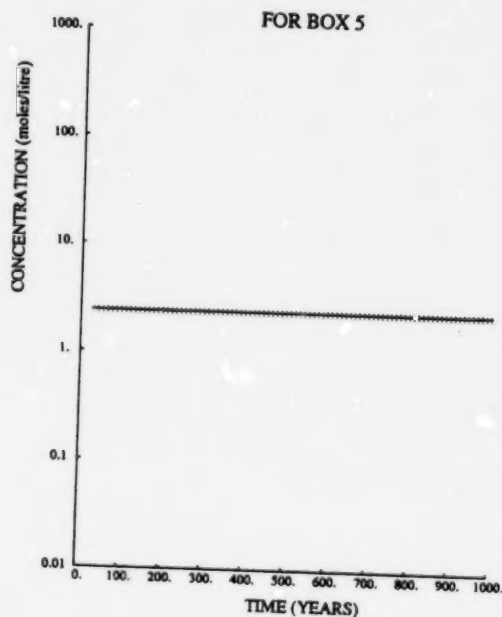


FIGURE E.2.8d CONCENTRATION vs. TIME
FOR PbSO_4
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

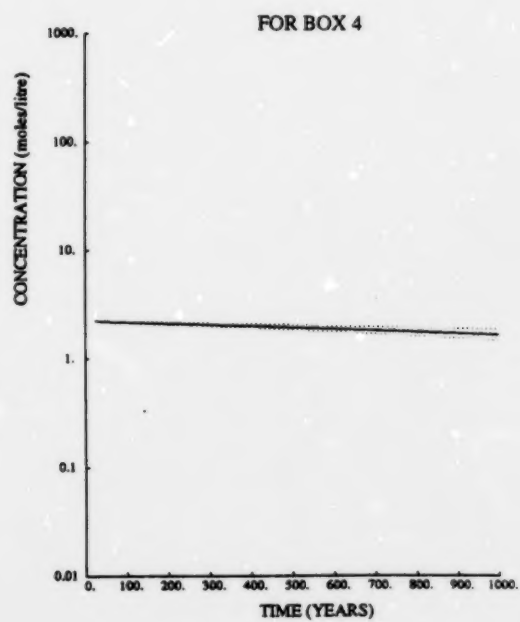
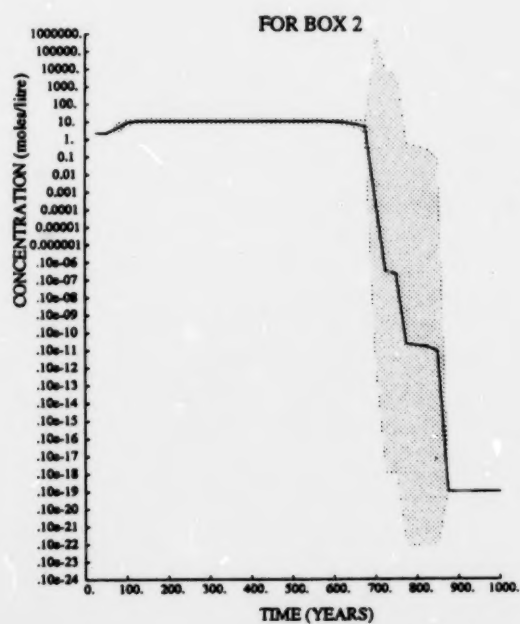
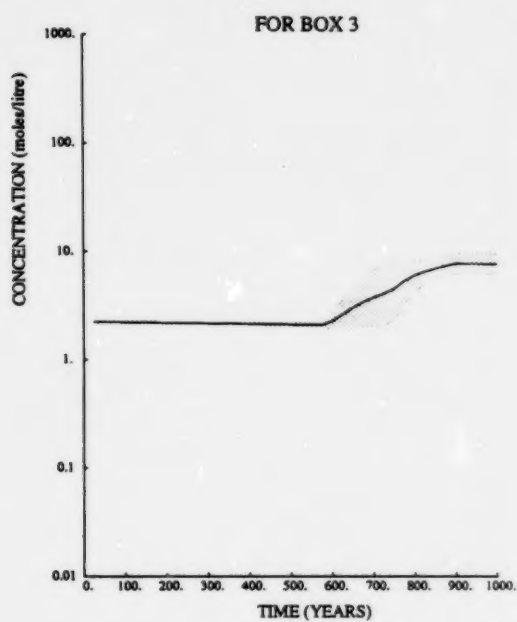
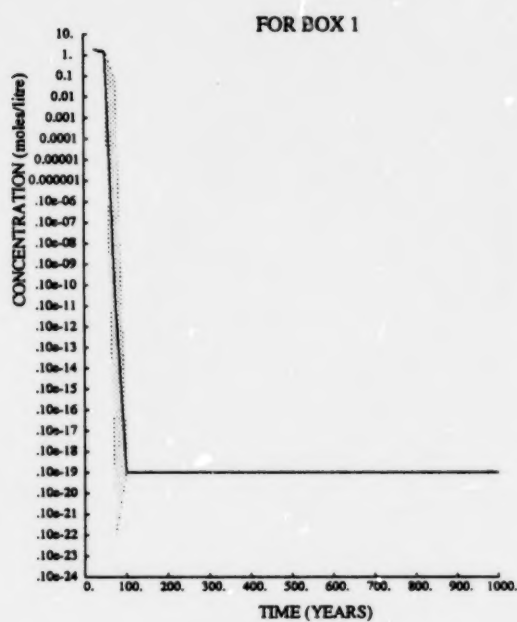


FIGURE E.2.8d CONCENTRATION vs. TIME
FOR PbSO₄
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

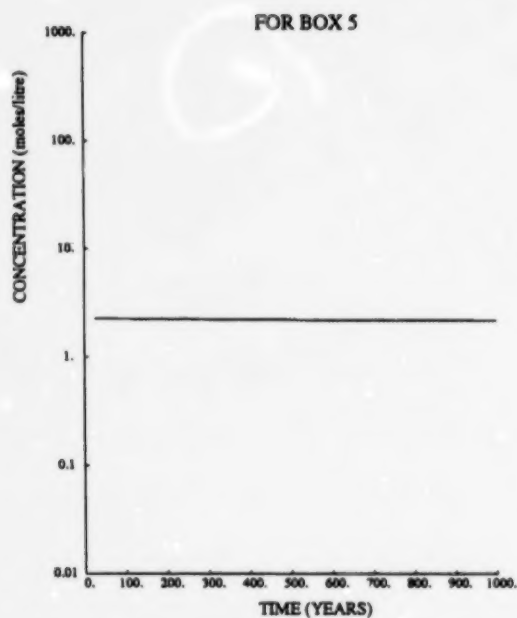


FIGURE E.2.9 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

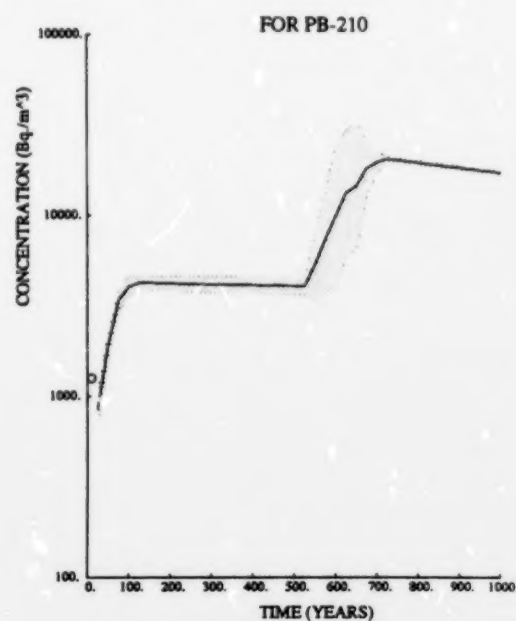
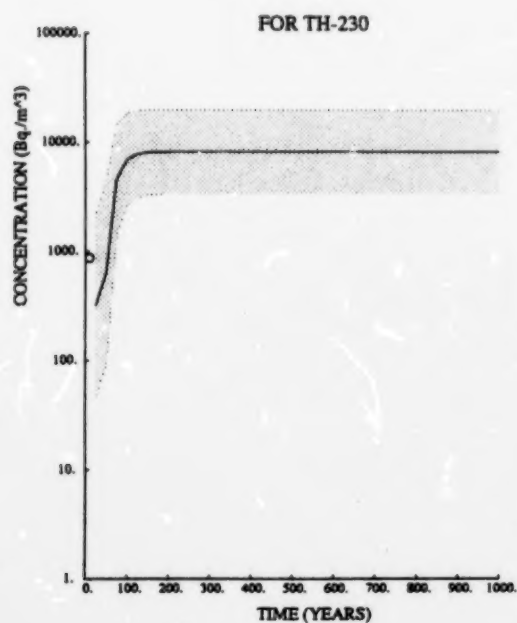
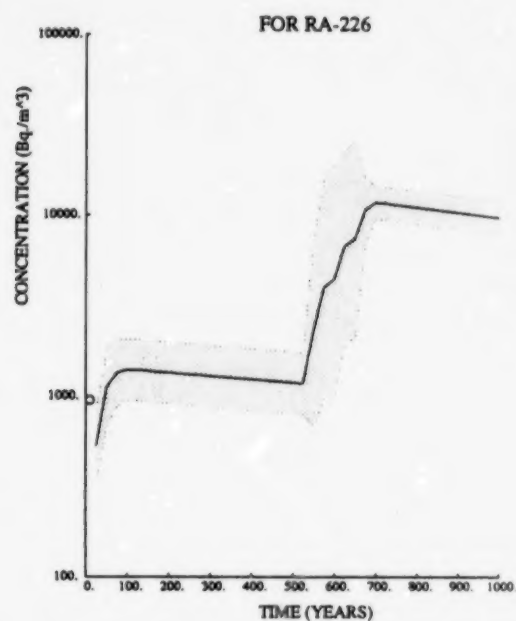
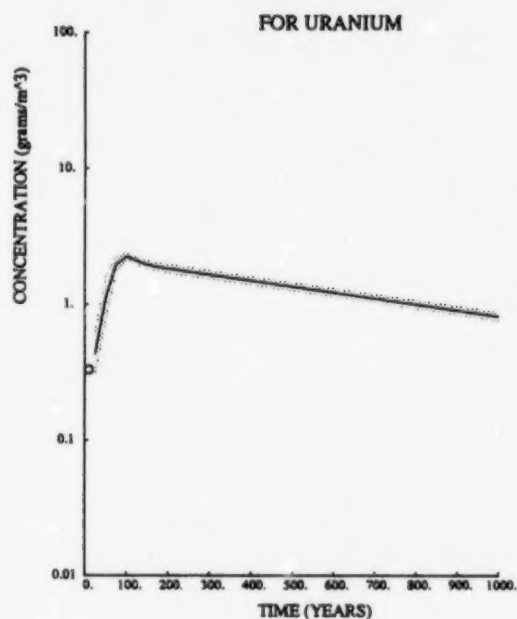


FIGURE E.2.9 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN DAM TOE S
GEOMETRIC MEAN OF 5 TRIALS

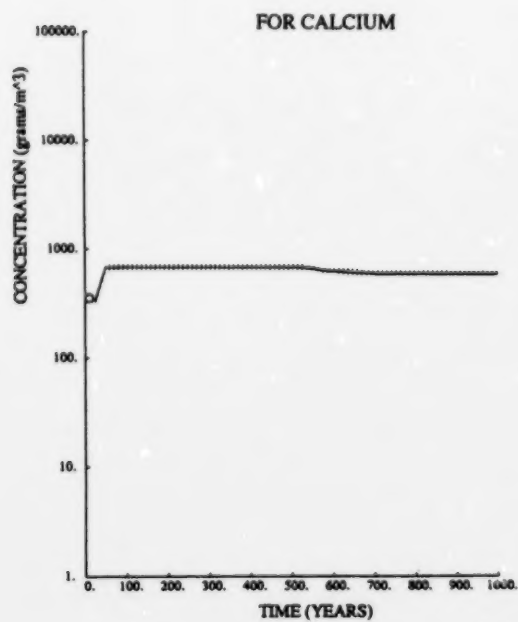
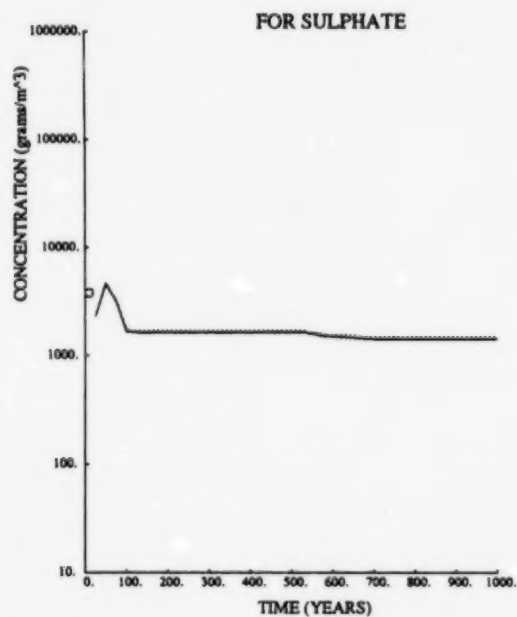


FIGURE E.2.10 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS

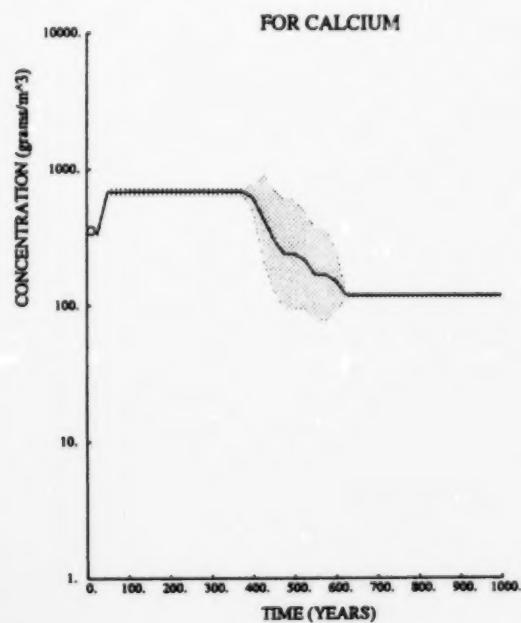
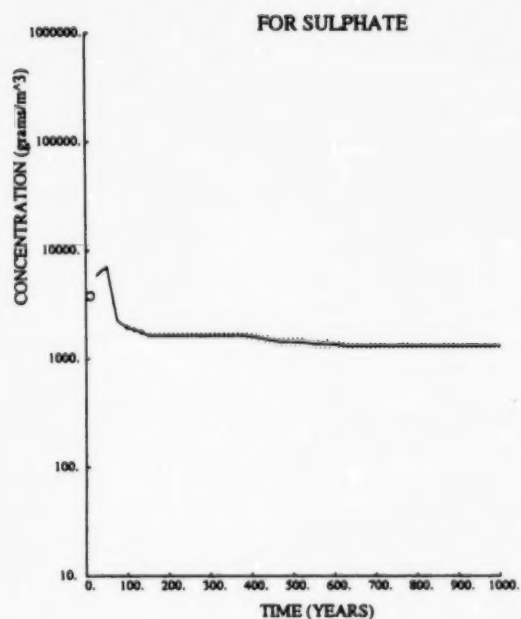
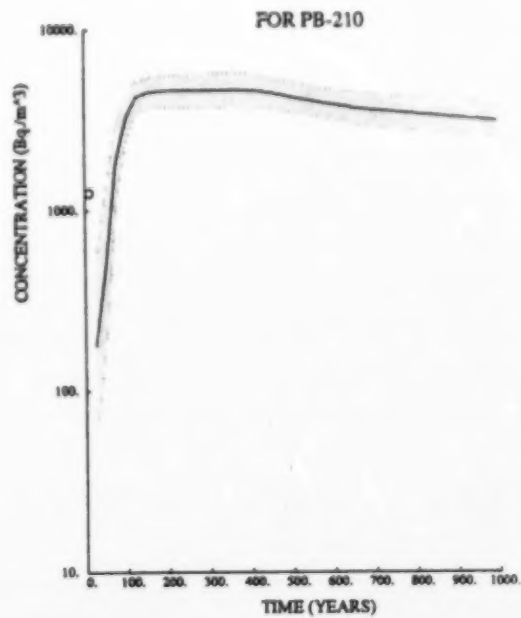
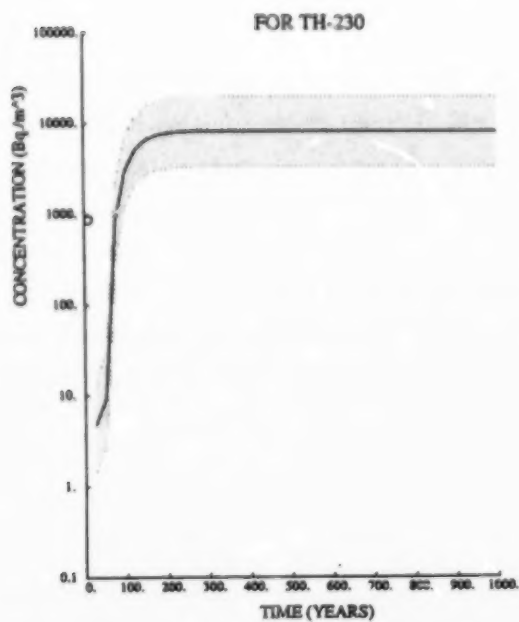
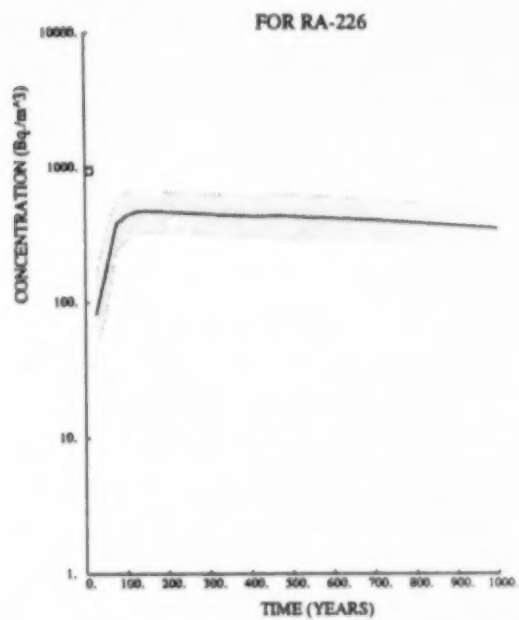
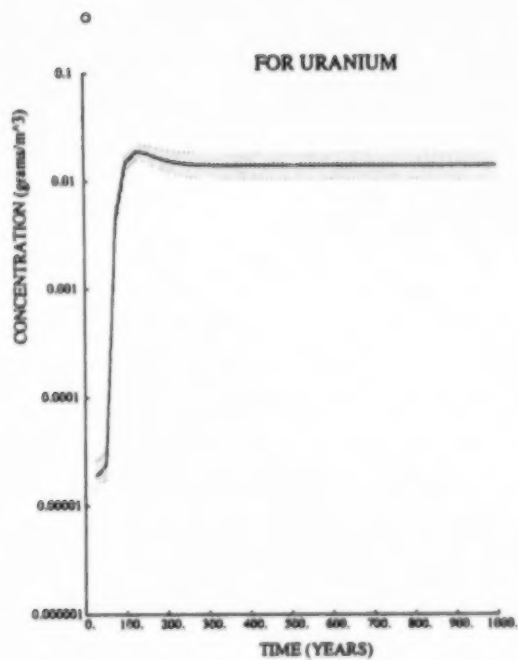


FIGURE E.2.10 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN DAM TOE N
GEOMETRIC MEAN OF 5 TRIALS



observed. This results from the small amount of weathering of UO_2 in the deeper box. A component from residual uranium in oxidized form could be added to the model.

For Th-230, the increase results from the breakthrough of Th-230 through the groundwater pathway. For Pb-210, the calculated values result from ingrowth from Ra-226 and an adsorption coefficient for Pb-210 which is lower than that for Ra-226. Most of the effect for Pb-210 results from ingrowth.

E.2.3 Lakes

Concentrations of the radionuclides in the three lakes are given in Figures E.2.11 (Parks Lake), E.2.12 (Hidden Bay) and E.2.13 (Wollaston Lake). The profiles for Parks Lake and Hidden Bay show essentially the same time trend for most radionuclides, but have different concentrations. The time trend predicted for each lake follows the time trend of the groundwater model. The different concentrations are caused mainly by the differences in hydrology - Parks Lake has a much smaller degree of dilution than does Hidden Bay. In addition, Hidden Bay is affected by exchange flow with Wollaston Lake. The values are reasonable in that they are within an order of magnitude of values for a conservative substance - sediment exchange removes the rest to the sediments. The predicted values cannot be compared to observed values because of the substantial input, from other background sources to Wollaston Lake.

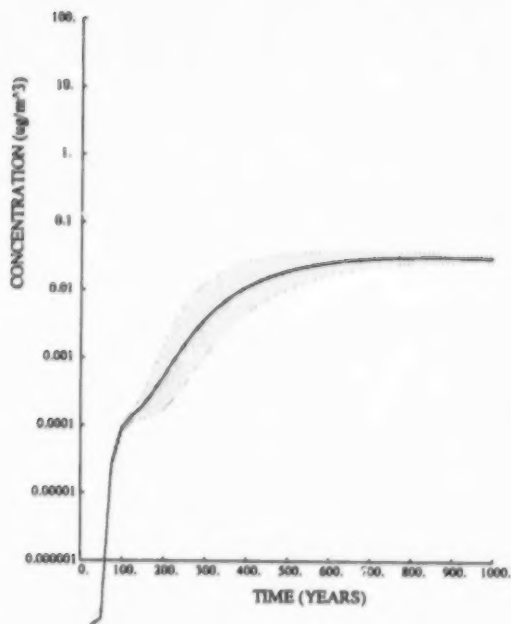
The calculated activity of radionuclides in Hidden Bay is of the same order of magnitude as that of Wollaston Lake, except for Th-230 which is an order of magnitude larger. These calculations agree with monitoring data which suggest that there is no detectable differences in uranium concentrations and radium-226 activity between the bay and the lake. Th-230 values are not well known due to detection limit values. The closeness of values reflects the effects of exchange flow between the lake and bay. The calculated activity of Pb-210 and Po-210 is reasonably close in Hidden Bay, but the values have larger differences in Wollaston Lake. These differences for Po-210 and Th-230 result from sediment-water interactions.

E.2.4 Atmospheric Concentrations

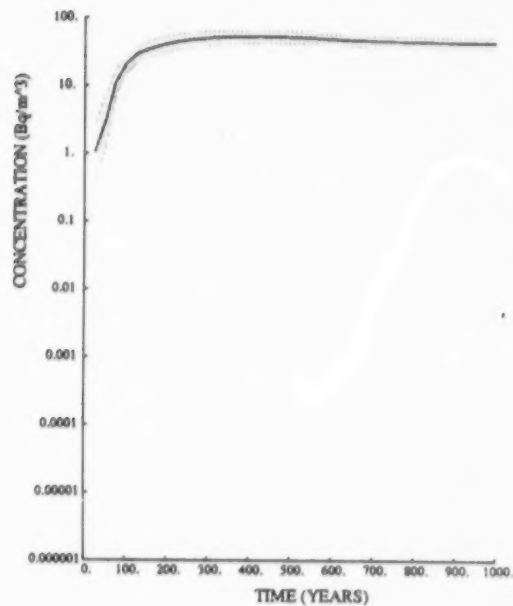
Atmospheric concentrations predicted at the Hidden Bay and Wollaston Lake locations of potential receptors are given in Figures E.2.14 (Hidden Bay) and E.2.15 (Wollaston

FIGURE E.2.11 CONCENTRATION vs. TIME
IN PARKS LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

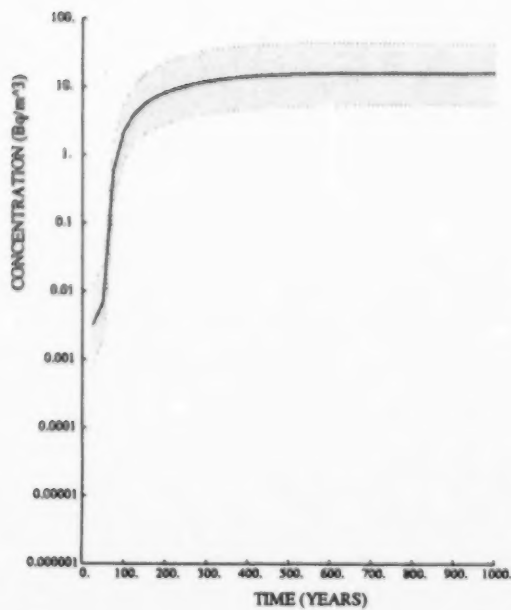
FOR U-238



FOR Ra-226



FOR Th-230



FOR Pb-210

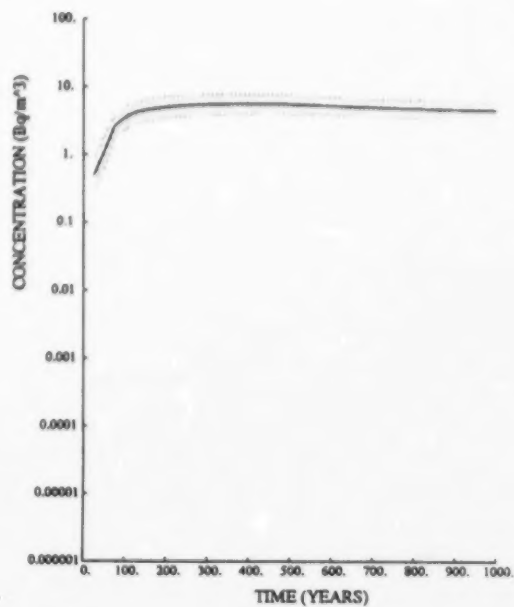


FIGURE E.2.11 CONCENTRATION vs. TIME
IN PARKS LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

FOR Po-210

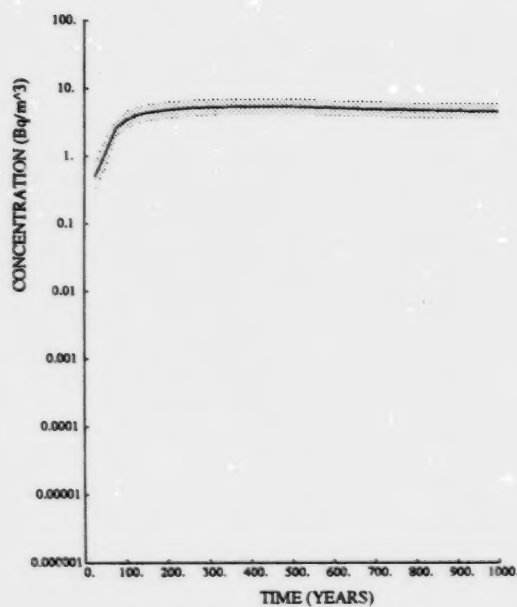
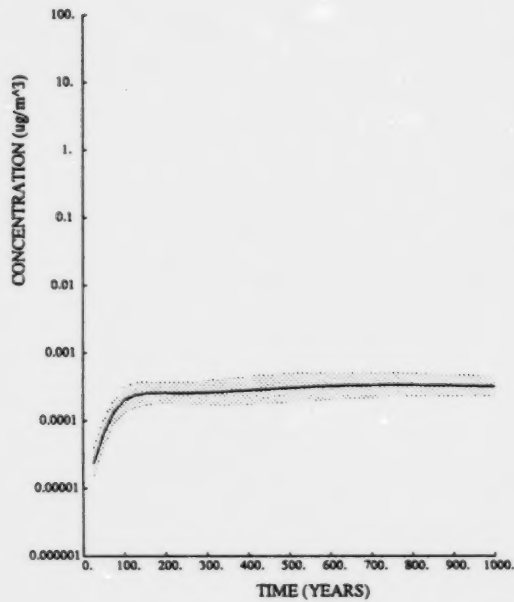
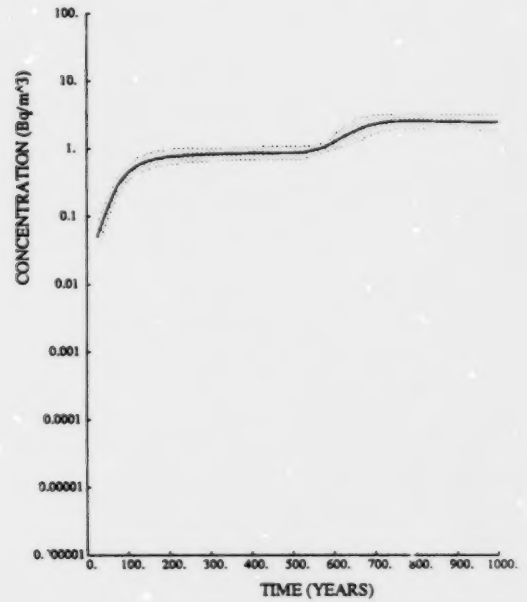


FIGURE E.2.12 CONCENTRATION vs. TIME
IN HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

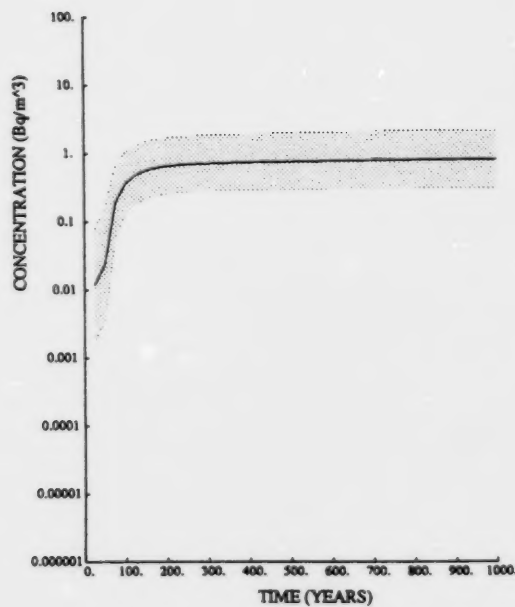
FOR U-238



FOR Ra-226



FOR Th-230



FOR Pb-210

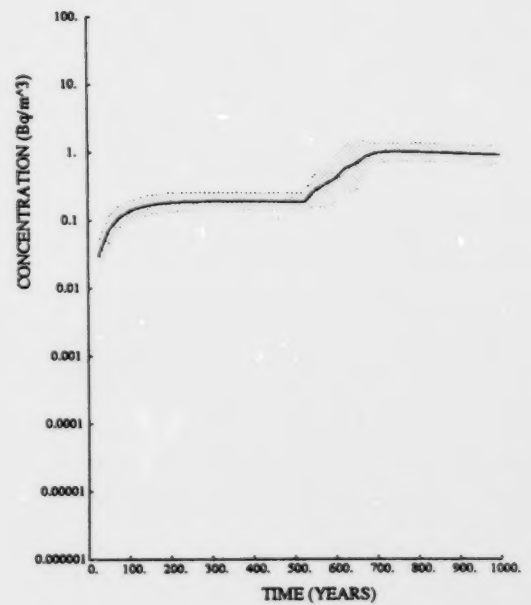


FIGURE E.2.12 CONCENTRATION vs. TIME
IN HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

FOR Po-210

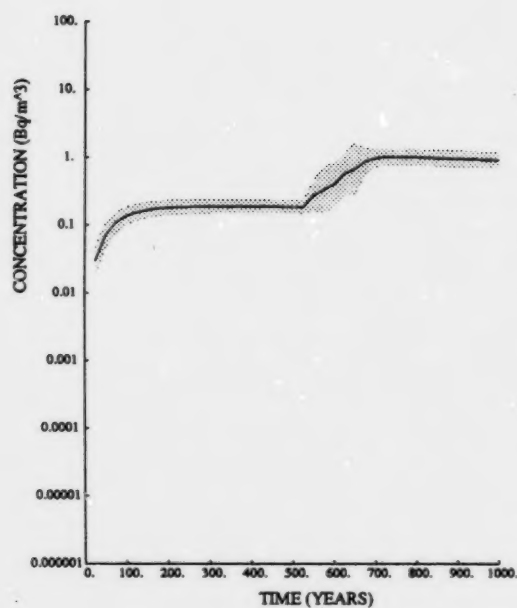
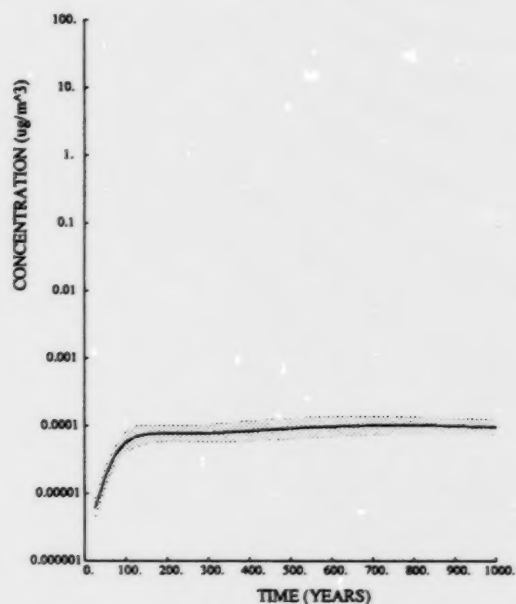
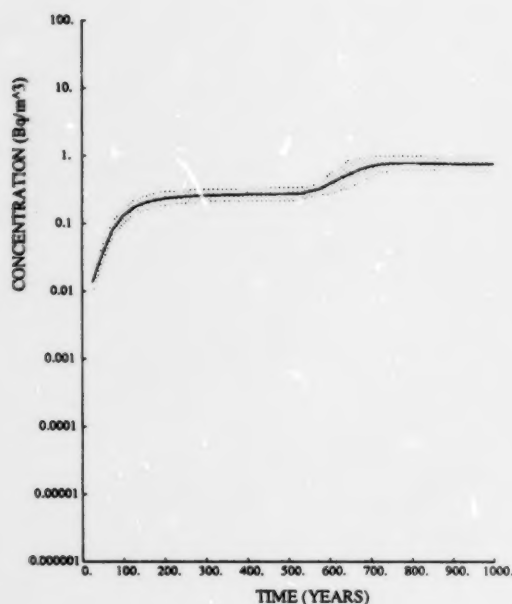


FIGURE E.2.13 CONCENTRATION vs. TIME
IN WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

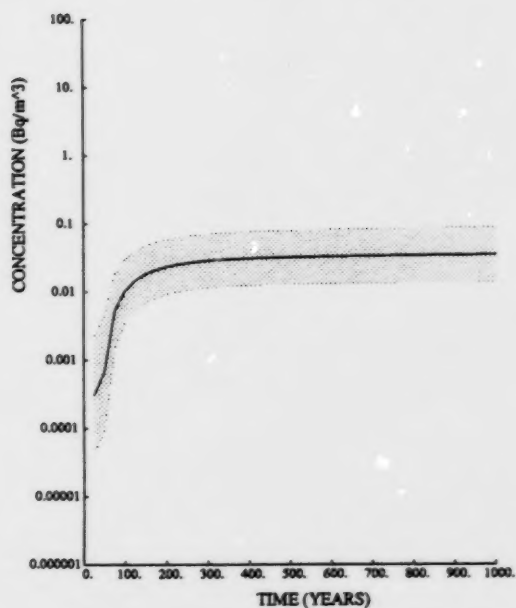
FOR U-238



FOR Ra-226



FOR Th-230



FOR Pb-210

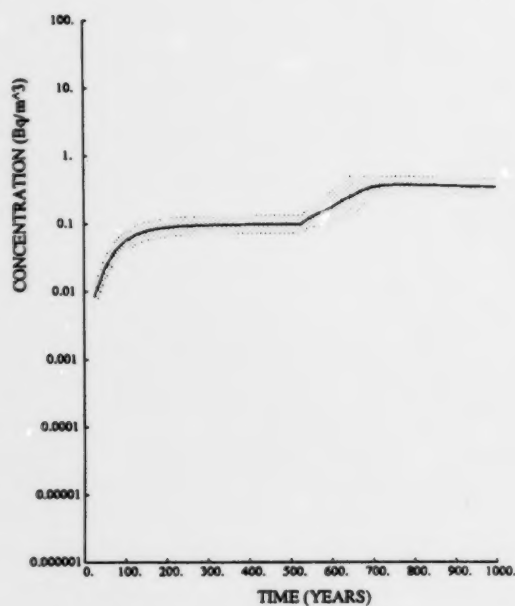


FIGURE E.2.13 CONCENTRATION vs. TIME
IN WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

FOR Po-210

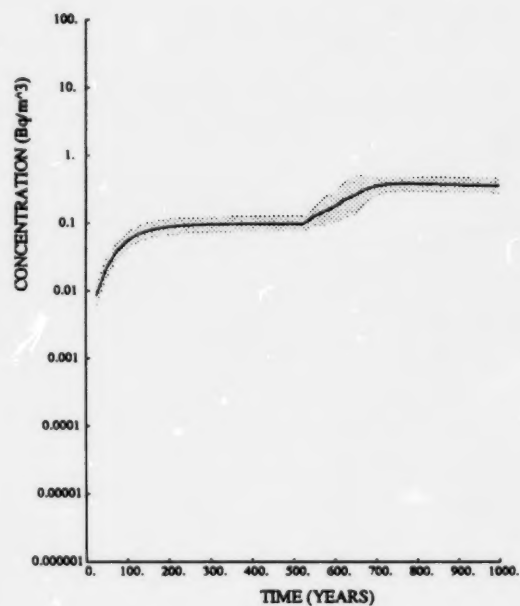


FIGURE E.2.14 CONCENTRATION vs. TIME
CAIR AT HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

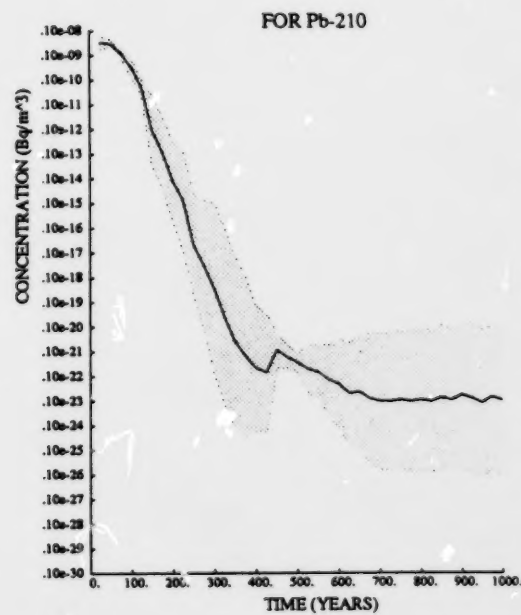
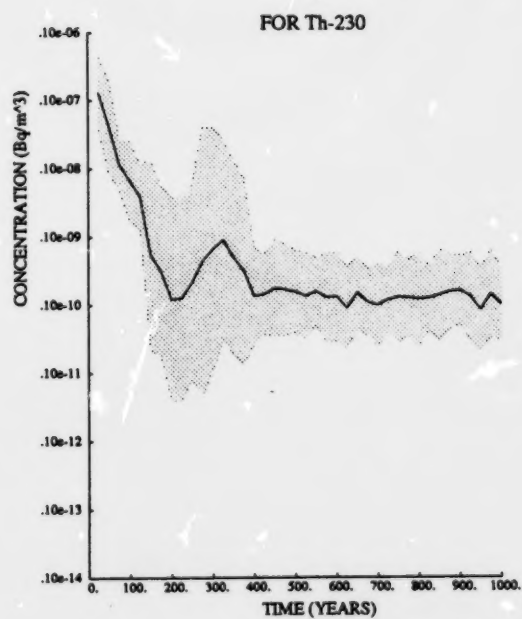
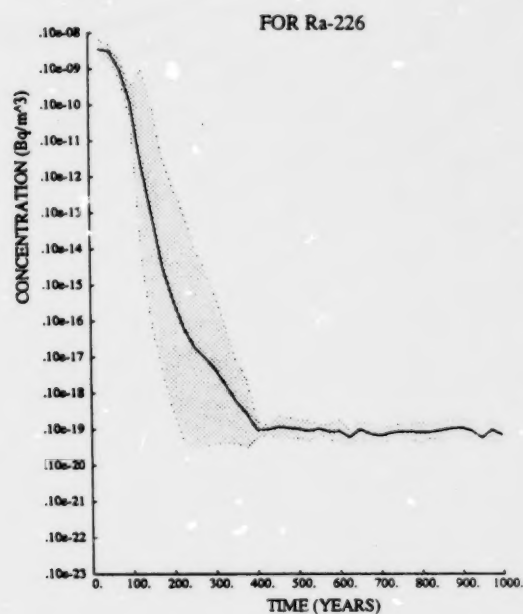
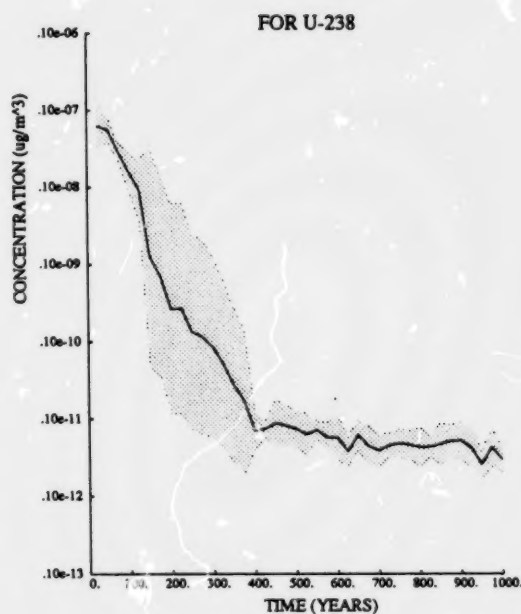


FIGURE E.2.14 CONCENTRATION vs. TIME
CAIR AT HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

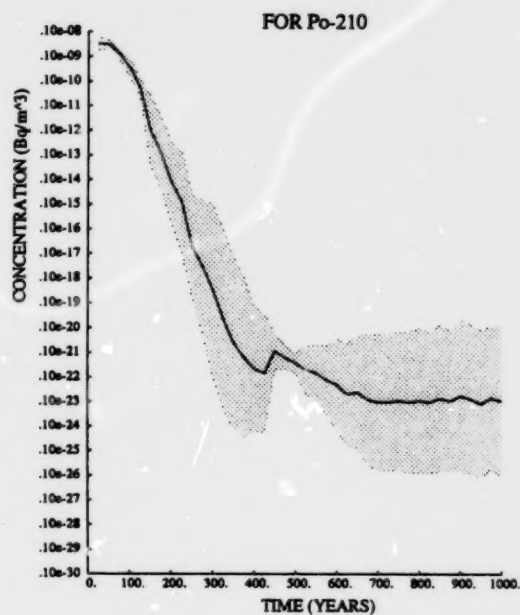


FIGURE E.2.15 CONCENTRATION vs. TIME
CAIR AT WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

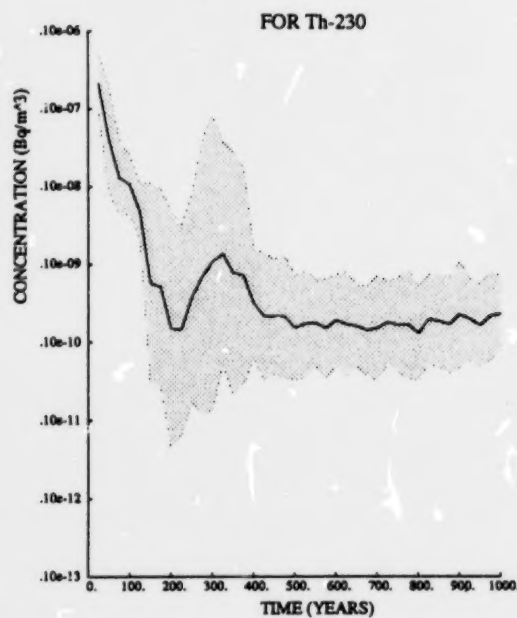
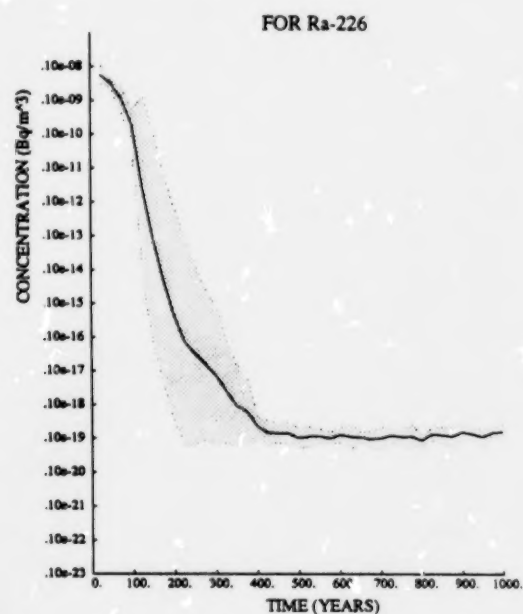
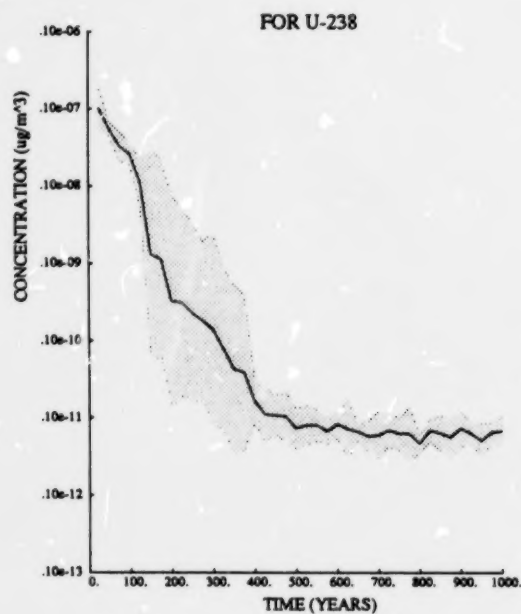


FIGURE E.2.15 CONCENTRATION vs. TIME
CAIR AT WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

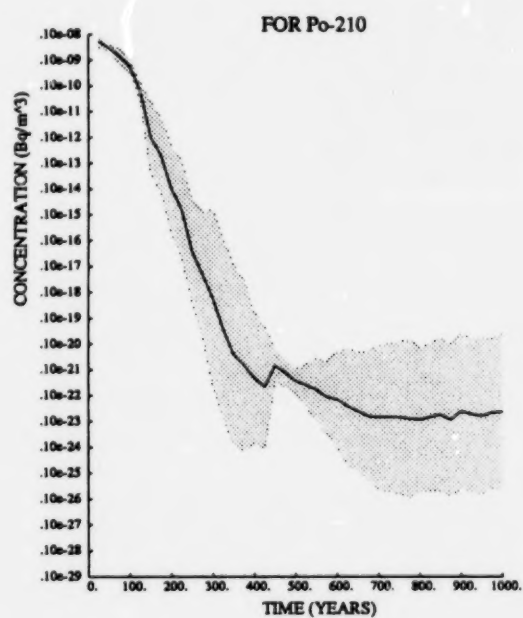


FIGURE E.2.16 CONCENTRATION vs. TIME
CAIR AT HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

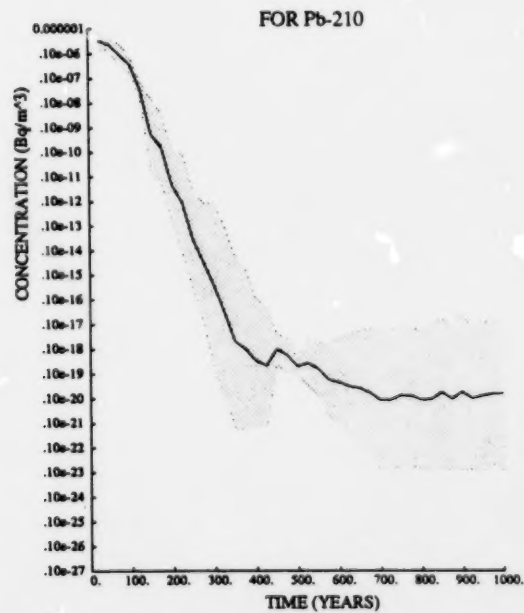
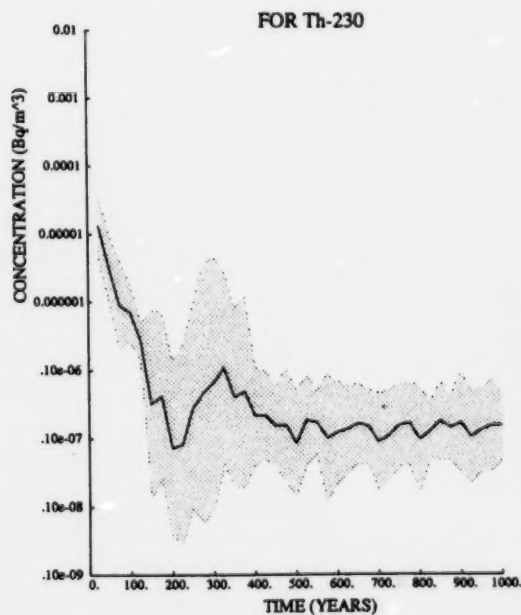
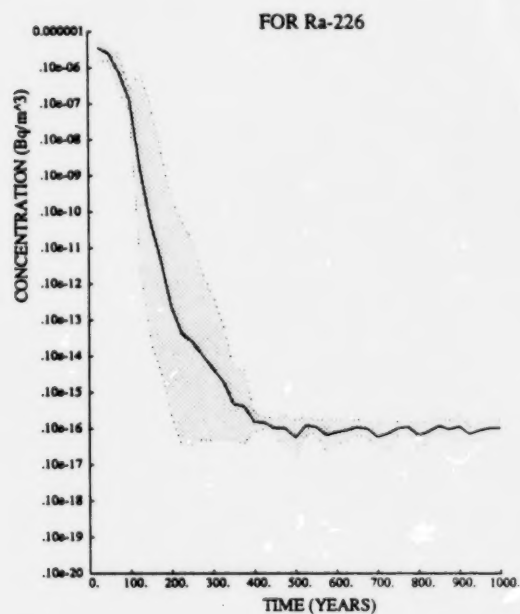
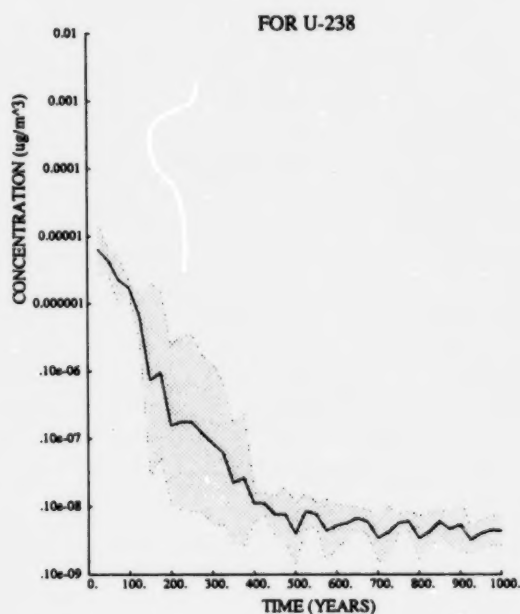


FIGURE E.2.16 CONCENTRATION vs. TIME
CAIR AT HIDDEN BAY
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

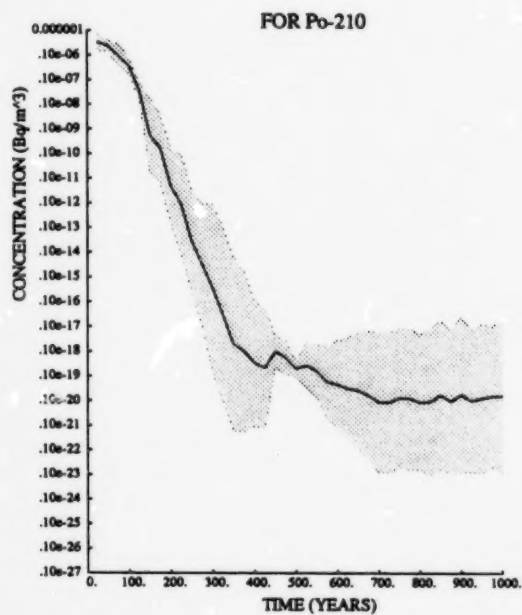


FIGURE E.2.17 CONCENTRATION vs. TIME
CAIR AT WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

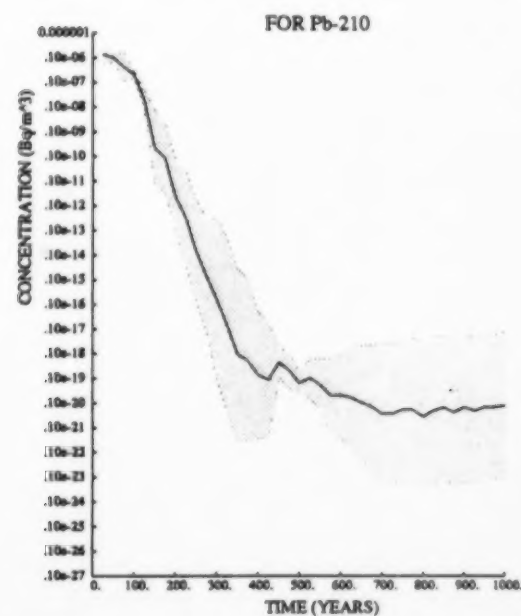
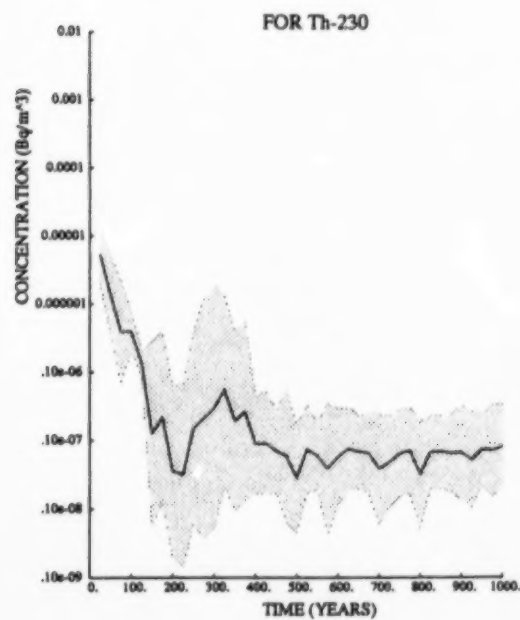
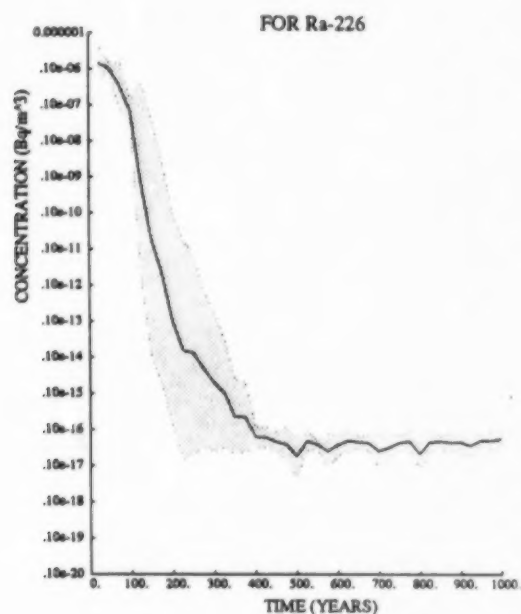
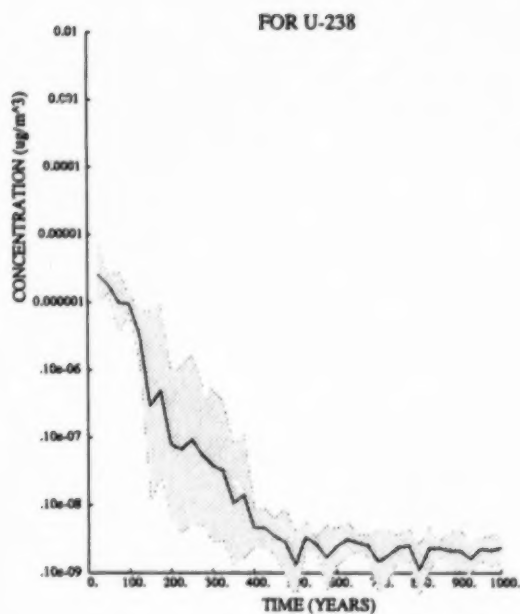
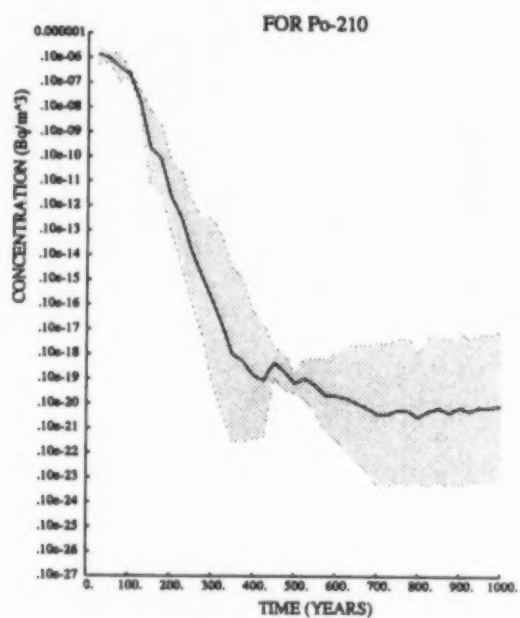


FIGURE E.2.17 CONCENTRATION vs. TIME
CAIR AT WOLLASTON LAKE
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS



Lake). This reflects the surficial concentration in the tailings. The calculations suggest the concentrations for most radionuclides are quite similar at the two sites, or that even the concentrations of Hidden Bay are somewhat higher than those at Wollaston Lake (e.g., the U-238 concentrations have a geometric mean of less than 10^{-8} for Hidden Bay, but slightly larger than 10^{-8} for Wollaston Lake at time 25 years.

These results initially suggested that the model was making erroneous calculations. It was subsequently decided that these calculations are correct because of the following examination.

The atmospheric concentrations calculated for each range and sector are given for five time periods in Table E 2.1 for uranium. The values circled are for Hidden Bay (Ring 2, Sector 11, a centroid distance of 7.5 km from the tailings) and Wollaston Lake (Ring 5, Sector 5, a centroid distance of 31 km from the tailings). The ranges correspond to the following distances:

<u>Range</u>	<u>Distance (km)</u>
1	1 to 6
2	6 to 9
3	9 to 18
4	18 to 27
5	27 to 36

The calculations of Table E2.1 indicate that sometimes the concentrations for Hidden Bay are larger for Wollaston Lake, but other times slightly smaller. However, within any sector, the calculation concentrations show a decrease with distance from the tailings source.

To examine this effect further, the concentrations at Hidden Bay (Figure E2.15) and Wollaston Lake (E2.16) were calculated assuming that the wind speed is similar in all directions (assigned in the Code as $UWIND(I,J) = UWIND(I,I)$) and that the frequency is the same in all directions (assigned as $FWIND2 = 1$). The concentrations in the various ranges and sectors are indicated in Table E2.2; the values for the Hidden Bay and Wollaston Lake receptor are circled. In this case, the air concentrations at Hidden Bay are always larger than at Wollaston Lake.

T= 100.00000

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.439e-06	0.195e-06	0.923e-07	0.459e-07	0.285e-07
2	0.143e-06	0.637e-07	0.303e-07	0.151e-07	0.936e-08
3	0.427e-07	0.191e-07	0.911e-08	0.456e-08	0.265e-08
4	0.181e-07	0.815e-08	0.393e-08	0.199e-08	0.125e-08
5	0.133e-06	0.607e-07	0.295e-07	0.151e-07	0.954e-08
6	0.138e-06	0.630e-07	0.307e-07	0.157e-07	0.989e-08
7	0.258e-06	0.961e-07	0.454e-07	0.229e-07	0.144e-07
8	0.108e-06	0.485e-07	0.233e-07	0.117e-07	0.731e-08
9	0.748e-07	0.335e-07	0.160e-07	0.803e-08	0.502e-08
10	0.257e-07	0.117e-07	0.564e-08	0.286e-08	0.180e-08
11	0.218e-07	0.981e-08	0.472e-08	0.239e-08	0.150e-08
12	0.236e-07	0.105e-07	0.501e-08	0.251e-08	0.156e-08
13	0.966e-07	0.429e-07	0.204e-07	0.102e-07	0.635e-08
14	0.223e-07	0.100e-07	0.481e-08	0.242e-08	0.152e-08
15	0.154e-07	0.687e-08	0.328e-08	0.164e-08	0.103e-08
16	0.431e-07	0.191e-07	0.905e-08	0.450e-08	0.280e-08

Table E2.1

Aircon For Uranium Fraction of
Time and Wind

1 Particular Year (1972)

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.161e-07	0.729e-08	0.352e-08	0.178e-08	0.112e-08
2	0.396e-08	0.179e-08	0.864e-09	0.436e-09	0.276e-09
3	0.155e-08	0.703e-09	0.341e-09	0.173e-09	0.109e-09
4	0.507e-08	0.234e-08	0.115e-08	0.590e-09	0.375e-09
5	0.247e-07	0.115e-07	0.566e-08	0.293e-08	0.187e-08
6	0.346e-07	0.160e-07	0.789e-08	0.407e-08	0.259e-08
7	0.183e-07	0.835e-08	0.406e-08	0.207e-08	0.131e-08
8	0.774e-08	0.353e-08	0.172e-08	0.874e-09	0.552e-09
9	0.456e-08	0.207e-08	0.100e-08	0.508e-09	0.320e-09
10	0.128e-08	0.579e-09	0.280e-09	0.142e-09	0.894e-10
11	0.215e-08	0.751e-09	0.452e-09	0.226e-09	0.141e-09
12	0.198e-08	0.874e-09	0.414e-09	0.206e-09	0.128e-09
13	0.244e-08	0.109e-08	0.525e-09	0.264e-09	0.166e-09
14	0.129e-08	0.576e-09	0.278e-09	0.140e-09	0.880e-10
15	0.170e-08	0.763e-09	0.366e-09	0.185e-09	0.116e-09
16	0.110e-07	0.497e-08	0.240e-08	0.121e-08	0.762e-09

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.822e-10	0.375e-10	0.182e-10	0.927e-11	0.585e-11
2	0.262e-10	0.119e-10	0.572e-11	0.290e-11	0.182e-11
3	0.105e-10	0.479e-11	0.233e-11	0.119e-11	0.755e-12
4	0.344e-10	0.158e-10	0.773e-11	0.397e-11	0.252e-11
5	0.974e-10	0.449e-10	0.222e-10	0.113e-10	0.721e-11
6	0.129e-09	0.588e-10	0.287e-10	0.147e-10	0.927e-11
7	0.679e-10	0.308e-10	0.149e-10	0.760e-11	0.479e-11
8	0.440e-10	0.200e-10	0.967e-11	0.491e-11	0.309e-11
9	0.270e-10	0.123e-10	0.600e-11	0.306e-11	0.194e-11
10	0.874e-11	0.399e-11	0.193e-11	0.985e-12	0.622e-12
11	0.150e-10	0.675e-11	0.326e-11	0.165e-11	0.104e-11
12	0.271e-10	0.123e-10	0.597e-11	0.304e-11	0.192e-11
13	0.147e-10	0.668e-11	0.324e-11	0.165e-11	0.104e-11
14	0.909e-11	0.407e-11	0.195e-11	0.982e-12	0.615e-12
15	0.131e-10	0.583e-11	0.279e-11	0.140e-11	0.880e-12
16	0.302e-10	0.136e-10	0.670e-11	0.342e-11	0.216e-11

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.250e-10	0.113e-10	0.546e-11	0.777e-11	0.174e-11
2	0.614e-11	0.278e-11	0.134e-11	0.680e-12	0.428e-12
3	0.240e-11	0.109e-11	0.529e-12	0.269e-12	0.170e-12
4	0.787e-11	0.363e-11	0.178e-11	0.916e-12	0.582e-12
5	0.383e-10	0.178e-10	0.880e-11	0.455e-11	0.290e-11
6	0.537e-10	0.249e-10	0.122e-10	0.631e-11	0.402e-11
7	0.284e-10	0.130e-10	0.630e-11	0.321e-11	0.203e-11
8	0.120e-10	0.548e-11	0.266e-11	0.136e-11	0.857e-12
9	0.708e-11	0.321e-11	0.156e-11	0.789e-12	0.497e-12
10	0.198e-11	0.899e-12	0.435e-12	0.220e-12	0.139e-12
11	0.333e-11	0.148e-11	0.702e-12	0.350e-12	0.218e-12
12	0.308e-11	0.136e-11	0.642e-12	0.319e-12	0.198e-12
13	0.379e-11	0.170e-11	0.815e-12	0.411e-12	0.258e-12
14	0.200e-11	0.897e-12	0.431e-12	0.218e-12	0.137e-12
15	0.264e-11	0.119e-11	0.569e-12	0.287e-12	0.180e-12
16	0.171e-10	0.772e-11	0.372e-11	0.186e-11	0.118e-11

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.292e-10	0.131e-10	0.630e-11	0.318e-11	0.200e-11
2	0.248e-11	0.110e-11	0.522e-12	0.260e-12	0.162e-12
3	0.774e-12	0.343e-12	0.163e-12	0.815e-13	0.509e-13
4	0.142e-11	0.633e-12	0.302e-12	0.151e-12	0.944e-13
5	0.109e-10	0.507e-11	0.251e-11	0.130e-11	0.832e-12
6	0.170e-10	0.789e-11	0.390e-11	0.201e-11	0.126e-11
7	0.106e-10	0.488e-11	0.240e-11	0.123e-11	0.783e-12
8	0.415e-11	0.193e-11	0.957e-12	0.496e-12	0.317e-12
9	0.807e-12	0.357e-12	0.169e-12	0.846e-13	0.527e-13
10	0.217e-11	0.940e-12	0.437e-12	0.213e-12	0.131e-12
11	0.216e-11	0.962e-12	0.459e-12	0.230e-12	0.144e-12
12	0.572e-12	0.252e-12	0.119e-12	0.595e-13	0.370e-13
13	0.292e-11	0.129e-11	0.609e-12	0.303e-12	0.189e-12
14	0.205e-11	0.906e-12	0.430e-12	0.214e-12	0.133e-12
15	0.432e-11	0.201e-11	0.954e-12	0.476e-12	0.296e-12
16	0.149e-11	0.660e-11	0.314e-11	0.157e-11	0.977e-12

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.220e-04	0.105e-04	0.530e-05	0.280e-05	0.181e-05
2	0.129e-04	0.616e-05	0.311e-05	0.164e-05	0.106e-05
3	0.651e-05	0.311e-05	0.157e-05	0.830e-06	0.837e-06
4	0.368e-05	0.176e-05	0.886e-06	0.465e-06	0.303e-06
5	0.773e-05	0.463e-05	0.235e-05	0.124e-05	0.803e-06
6	0.109e-04	0.521e-05	0.263e-05	0.137e-05	0.893e-06
7	0.145e-04	0.573e-05	0.350e-05	0.185e-05	0.120e-05
8	0.104e-04	0.499e-05	0.252e-05	0.133e-05	0.861e-06
9	0.844e-05	0.403e-05	0.204e-05	0.108e-05	0.677e-06
10	0.432e-05	0.206e-05	0.104e-05	0.550e-06	0.356e-06
11	0.335e-05	0.160e-05	0.809e-06	0.427e-06	0.277e-06
12	0.406e-05	0.174e-05	0.980e-06	0.518e-06	0.335e-06
13	0.838e-05	0.400e-05	0.202e-05	0.107e-05	0.671e-06
14	0.348e-05	0.166e-05	0.840e-06	0.444e-06	0.287e-06
15	0.303e-05	0.145e-05	0.731e-06	0.386e-06	0.250e-06
16	0.522e-05	0.250e-05	0.126e-05	0.665e-06	0.431e-06
T=	220.0000				

Table E2.2

Atmospheric Concentrations (AIR)
With All FWIND2 = 1 and
UWIND(I,J) = UWIND

For Uranium Only

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.755e-06	0.456e-06	0.230e-06	0.122e-06	0.788e-07
2	0.515e-06	0.246e-06	0.124e-06	0.656e-07	0.424e-07
3	0.336e-06	0.161e-06	0.810e-07	0.428e-07	0.277e-07
4	0.557e-06	0.266e-06	0.134e-06	0.709e-07	0.457e-07
5	0.120e-05	0.571e-06	0.258e-06	0.152e-06	0.966e-07
6	0.148e-05	0.707e-06	0.357e-06	0.188e-06	0.122e-06
7	0.119e-05	0.566e-06	0.286e-06	0.151e-06	0.978e-07
8	0.796e-06	0.381e-06	0.192e-06	0.102e-06	0.658e-07
9	0.567e-06	0.271e-06	0.137e-06	0.722e-07	0.467e-07
10	0.252e-06	0.122e-06	0.605e-07	0.321e-07	0.206e-07
11	0.399e-06	0.190e-06	0.962e-07	0.538e-07	0.329e-07
12	0.376e-06	0.185e-06	0.911e-07	0.481e-07	0.312e-07
13	0.366e-06	0.176e-06	0.867e-07	0.468e-07	0.303e-07
14	0.262e-06	0.125e-06	0.632e-07	0.334e-07	0.216e-07
15	0.304e-06	0.145e-06	0.734e-07	0.388e-07	0.251e-07
16	0.829e-06	0.396e-06	0.200e-06	0.106e-06	0.683e-07
T=	400.0000				

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.460e-08	0.220e-08	0.111e-08	0.586e-09	0.380e-09
2	0.300e-08	0.143e-08	0.723e-09	0.382e-09	0.247e-09
3	0.167e-08	0.798e-09	0.403e-09	0.213e-09	0.138e-09
4	0.362e-08	0.173e-08	0.873e-09	0.461e-09	0.299e-09
5	0.613e-08	0.293e-08	0.148e-08	0.781e-09	0.506e-09
6	0.739e-08	0.353e-08	0.178e-08	0.941e-09	0.607e-09
7	0.557e-08	0.266e-08	0.134e-08	0.710e-09	0.460e-09
8	0.446e-08	0.213e-08	0.108e-08	0.568e-09	0.368e-09
9	0.278e-08	0.133e-08	0.671e-09	0.355e-09	0.230e-09
10	0.146e-08	0.699e-09	0.353e-09	0.187e-09	0.121e-09
11	0.223e-08	0.106e-08	0.538e-09	0.284e-09	0.184e-09
12	0.313e-08	0.150e-08	0.756e-09	0.399e-09	0.259e-09
13	0.181e-08	0.865e-09	0.437e-09	0.231e-09	0.149e-09
14	0.167e-08	0.799e-09	0.404e-09	0.213e-09	0.138e-09
15	0.223e-08	0.107e-08	0.538e-09	0.284e-09	0.184e-09
16	0.278e-08	0.133e-08	0.671e-09	0.355e-09	0.230e-09
T=	600.0000				

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.148e-08	0.708e-09	0.358e-09	0.189e-09	0.122e-09
2	0.799e-09	0.382e-09	0.193e-09	0.102e-09	0.657e-10
3	0.522e-09	0.249e-09	0.126e-09	0.665e-10	0.430e-10
4	0.865e-09	0.413e-09	0.209e-09	0.110e-09	0.713e-10
5	0.186e-08	0.887e-09	0.448e-09	0.237e-09	0.153e-09
6	0.230e-08	0.110e-08	0.554e-09	0.293e-09	0.189e-09
7	0.134e-08	0.879e-09	0.444e-09	0.235e-09	0.152e-09
8	0.124e-08	0.592e-09	0.299e-09	0.158e-09	0.102e-09
9	0.880e-09	0.420e-09	0.212e-09	0.112e-09	0.726e-10
10	0.391e-09	0.187e-09	0.943e-10	0.498e-10	0.323e-10
11	0.619e-09	0.296e-09	0.149e-09	0.789e-10	0.511e-10
12	0.587e-09	0.280e-09	0.141e-09	0.747e-10	0.484e-10
13	0.571e-09	0.273e-09	0.138e-09	0.727e-10	0.471e-10
14	0.407e-09	0.194e-09	0.981e-10	0.518e-10	0.336e-10
15	0.473e-09	0.226e-09	0.114e-09	0.602e-10	0.390e-10
16	0.129e-08	0.615e-09	0.310e-09	0.164e-09	0.106e-09
T=	1000.0000				

ATMOSPHERIC CONCENTRATION OF THE RADIONUCLIDES IN EACH SECTOR

RAD SECTOR	RING 1	2	3	4	5
1	0.128e-08	0.611e-09	0.308e-09	0.163e-09	0.105e-09
2	0.495e-09	0.236e-09	0.119e-09	0.630e-10	0.408e-10
3	0.248e-09	0.118e-09	0.597e-10	0.316e-10	0.204e-10
4	0.412e-09	0.197e-09	0.995e-10	0.525e-10	0.340e-10
5	0.495e-09	0.236e-09	0.119e-09	0.630e-10	0.408e-10
6	0.990e-09	0.473e-09	0.239e-09	0.126e-09	0.816e-10
7	0.907e-09	0.433e-09	0.219e-09	0.116e-09	0.748e-10
8	0.495e-09	0.236e-09	0.119e-09	0.630e-10	0.408e-10
9	0.165e-09	0.787e-10	0.397e-10	0.210e-10	0.136e-10
10	0.412e-09	0.197e-09	0.995e-10	0.525e-10	0.340e-10
11	0.330e-09	0.158e-09	0.796e-10	0.421e-10	0.272e-10
12	0.624e-10	0.393e-10	0.199e-10	0.105e-10	0.679e-11
13	0.330e-09	0.158e-09	0.796e-10	0.421e-10	0.272e-10
14	0.371e-09	0.177e-09	0.895e-10	0.473e-10	0.306e-10
15	0.784e-09	0.374e-09	0.189e-09	0.998e-10	0.646e-10
16	0.128e-08	0.611e-09	0.308e-09	0.163e-09	0.105e-09

Accordingly, the calculations of Figures E2.14 and E2.15 are correct. The effects of concentration at a receptor near to the tailings being larger than those further from the tailings is caused by the effects of frequency of wind direction and the spectrum of wind speeds.

E.2.5 Soil Concentrations

The calculated soil concentrations are given in Figure E2.18 for the Hidden Bay receptor and Figure E2.19 for the Wollaston Lake receptor for U-238, Th-232, Pb-210, Po-210 and Ra-226 for the three soil layers. The calculated activity at the Wollaston Lake site is slightly higher than at the Hidden Bay site, reflecting the slightly higher calculated air concentrations at Wollaston Lake. The data show an increase over the first several years and a plateau effect thereafter; this results from the decrease in atmospheric loadings. The calculated activity in the top layer is a couple of orders of magnitude lower than the middle (2) and bottom (3) layers, reflecting the initially high depositional rate from the air, and then a decreased depositional rate from the top soil horizon to the bottom layer, and accumulation in the bottom layer.

E.3 Sensitivity Analysis of Walk-through

One set of conditions were subjected to alterations of concentrations in the groundwater flowing from the east ridge through the tailings. The concentrations assumed were those in which the inflow concentrations were zero (Set 1) and those of Parks Lake (Set 2). The concentration values of Set 2 used concentrations measured in Parks Lake as the analogue for the groundwater concentrations. The results are given in Figures E3.1 for Box 3 and E3.2 for Box 7 for the case of no inflow concentration, and in Figures E3.3 for Box 3 and E3.4 for Box 7 for the case of higher concentrations.

The results for the no inflow case are similar to those of the base case. However, for the case with higher inflow concentrations of radium-226 and Pb-210, the porewater concentrations decrease for both Boxes 3 (Figure E3.3) and Box 7 (Figure E3.4). In fact, the calculated activity of Ra-226 leaving the tailings for the higher inflow case is lower.

Intuitively, the calculated results do not make sense. However, examination of the inflow concentrations and the calculated solid phase concentrations provide an explanation. The

FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 1 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

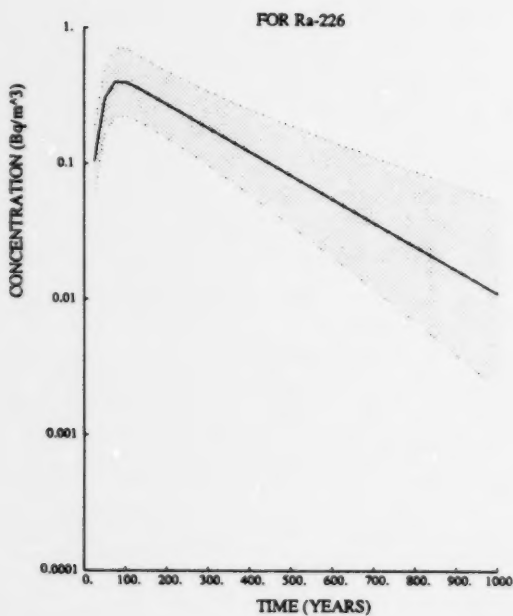
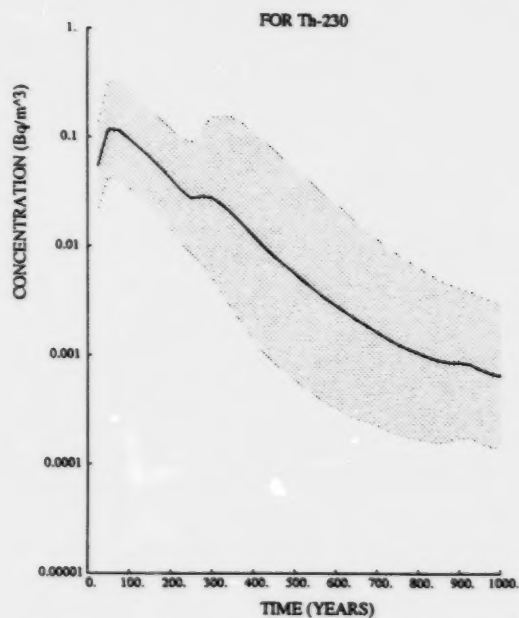
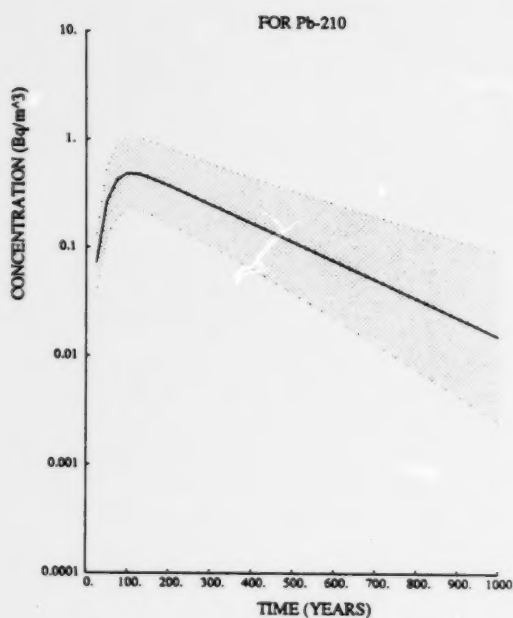
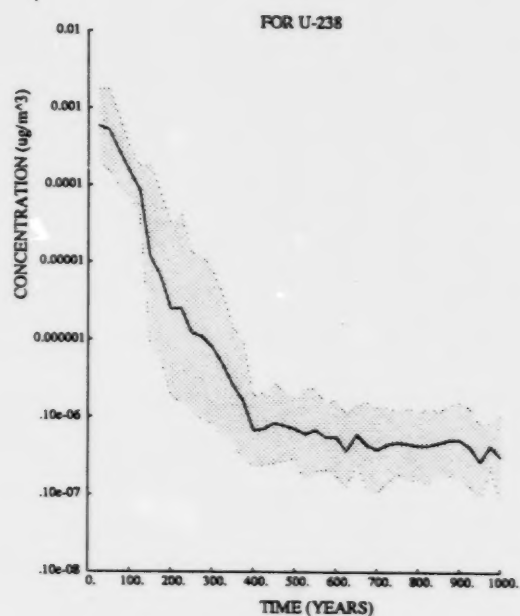


FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 1 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

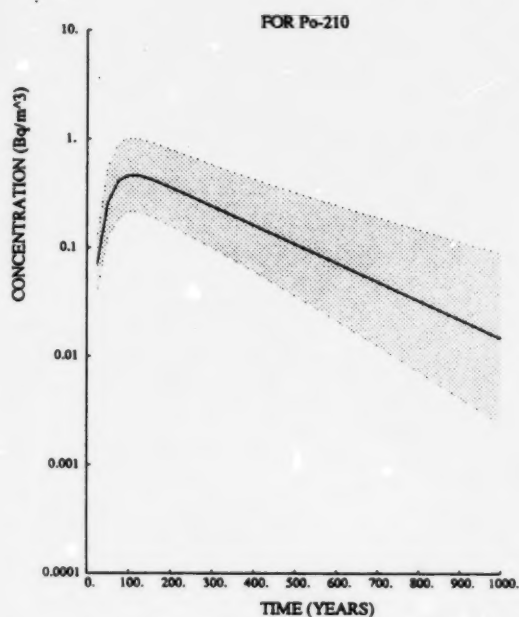


FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 2 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

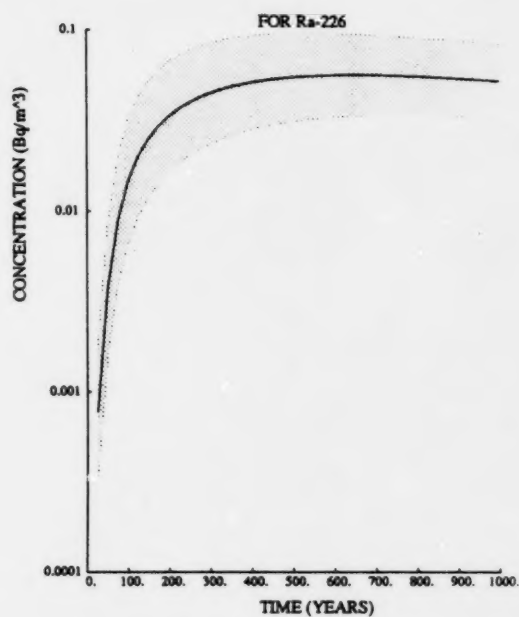
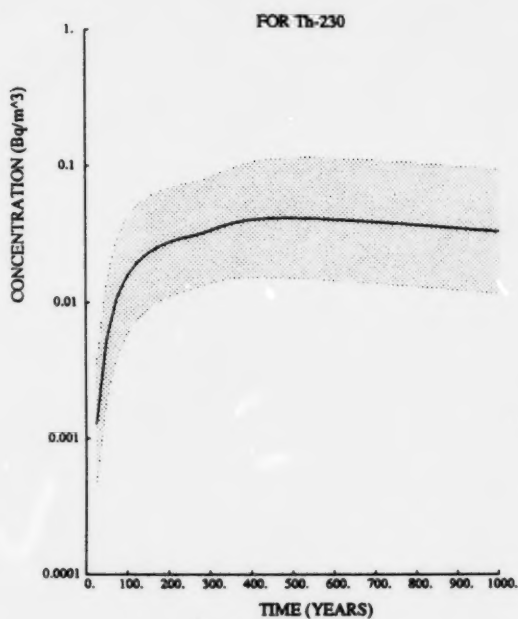
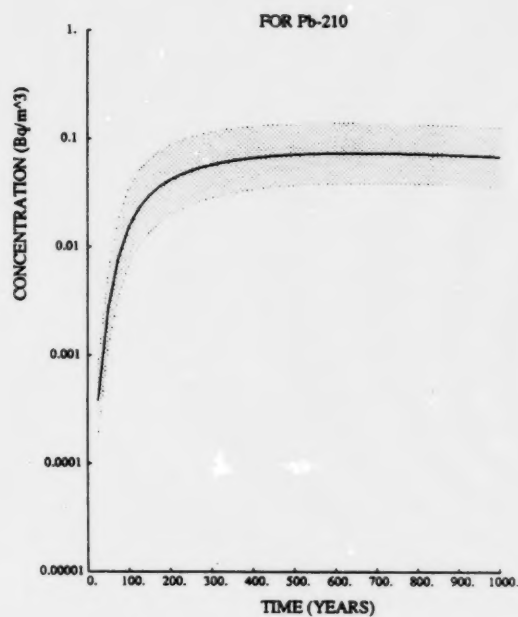
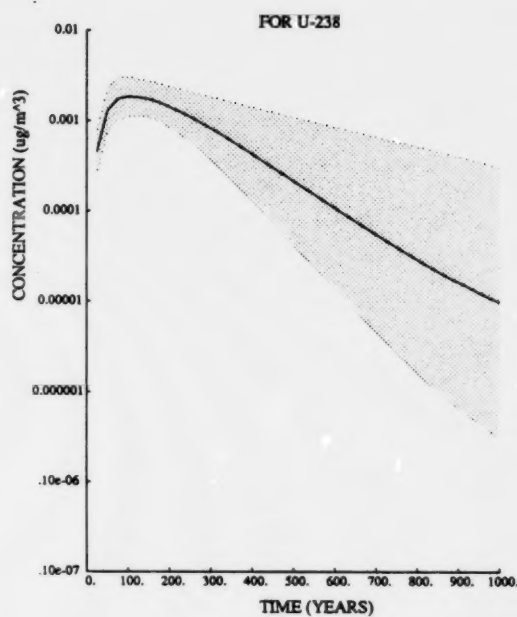


FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 2 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

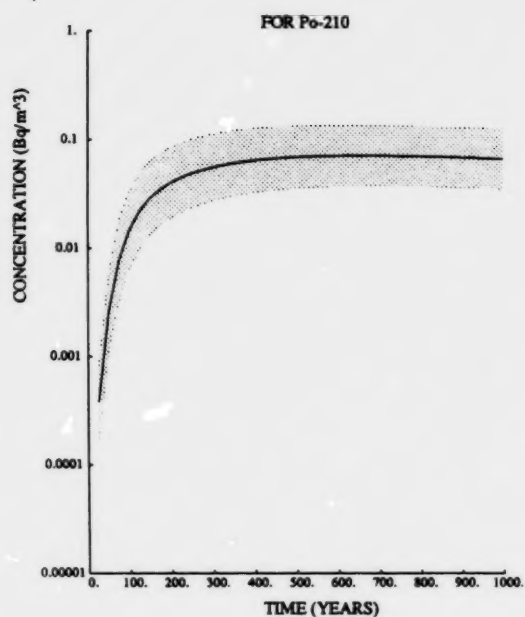


FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 3 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

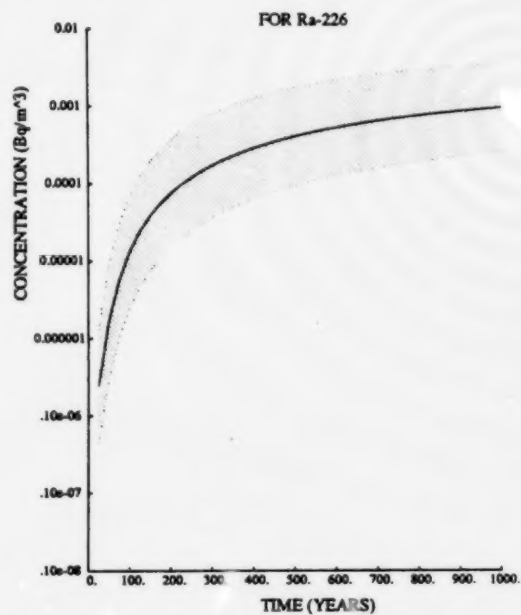
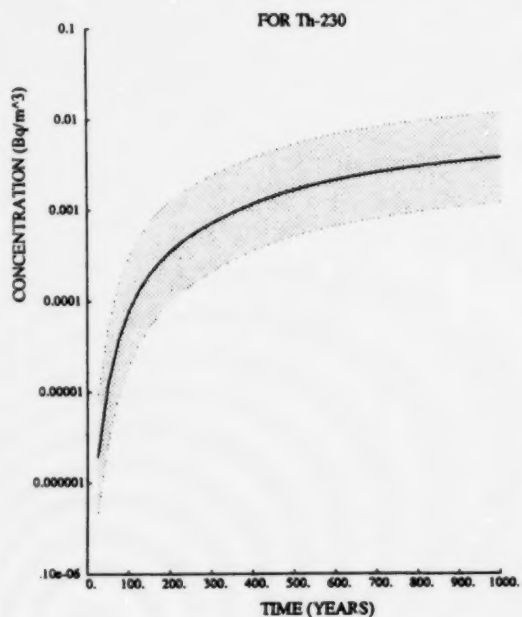
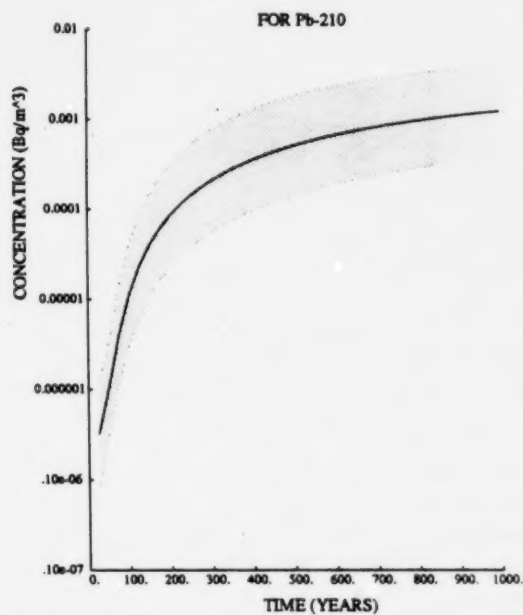
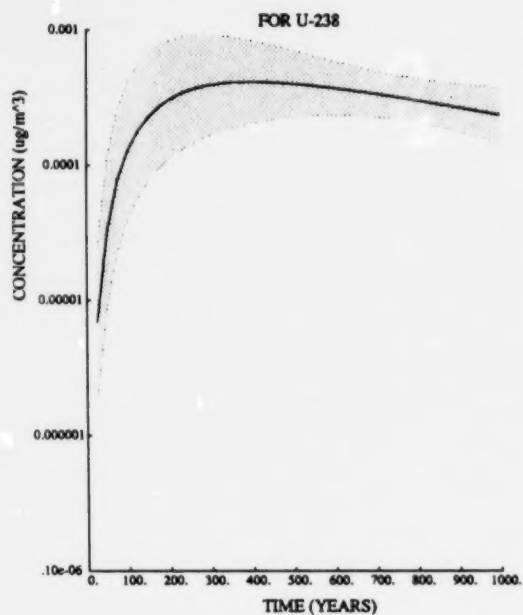


FIGURE E.2.18 SOIL CONCENTRATION vs. TIME
IN LAYER 3 AT HIDDEN BAY RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

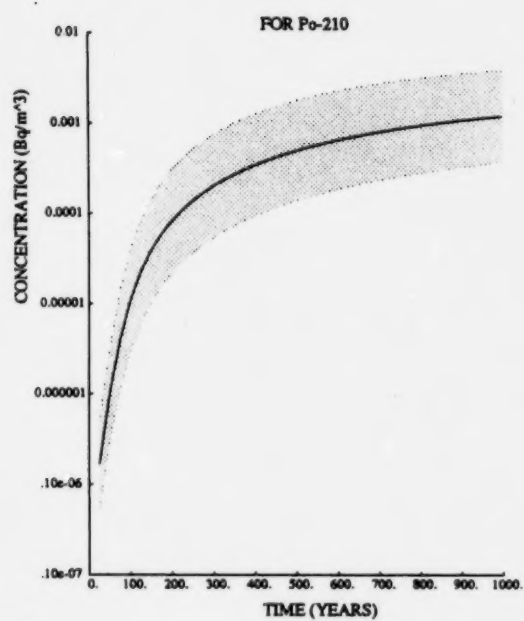


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 1 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

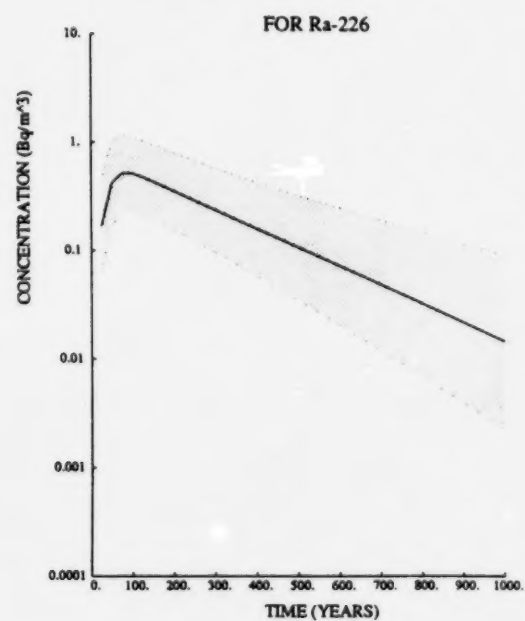
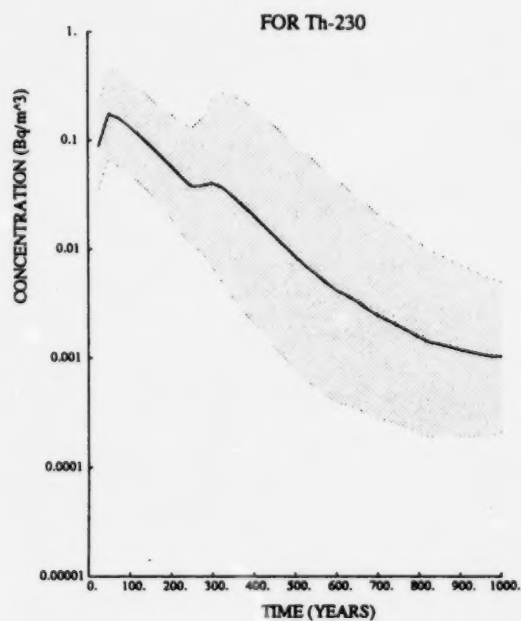
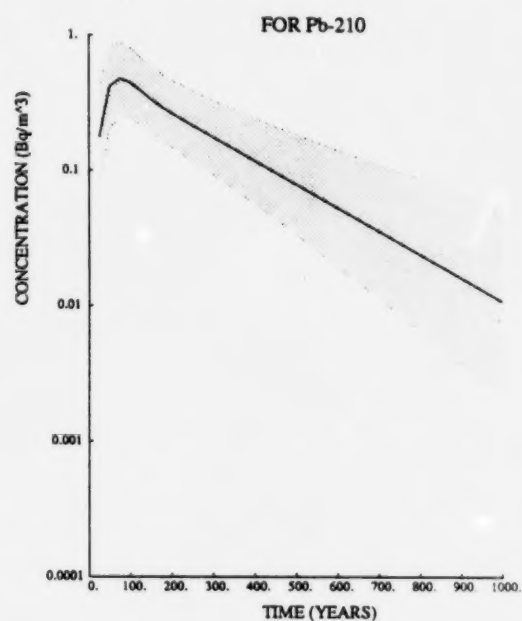
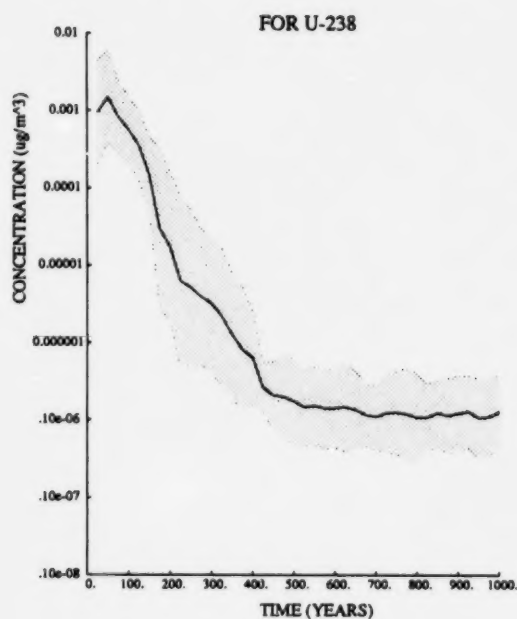


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 1 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

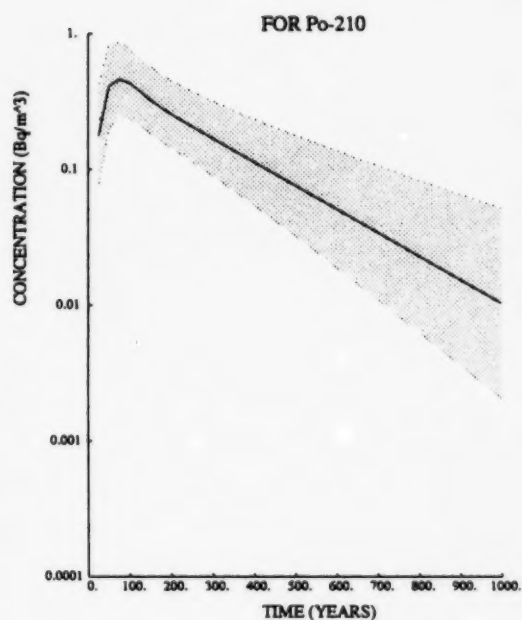


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 2 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

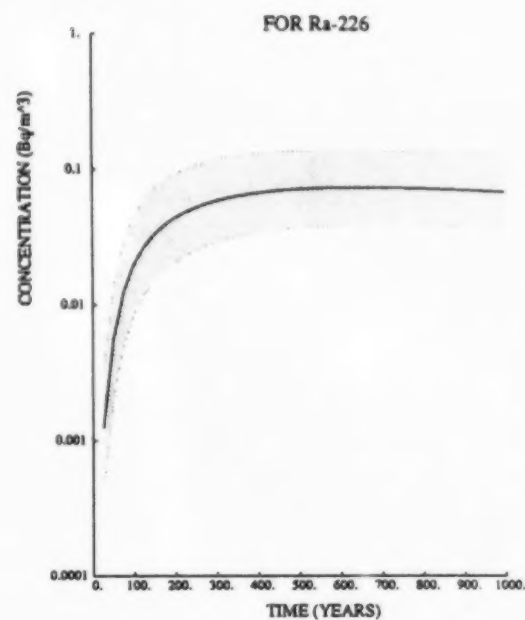
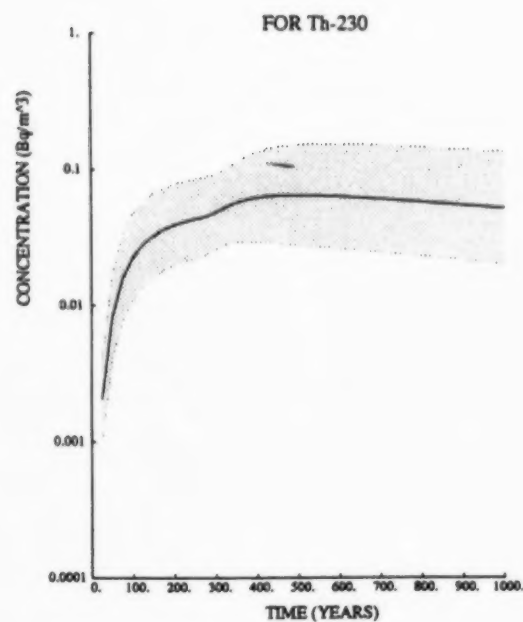
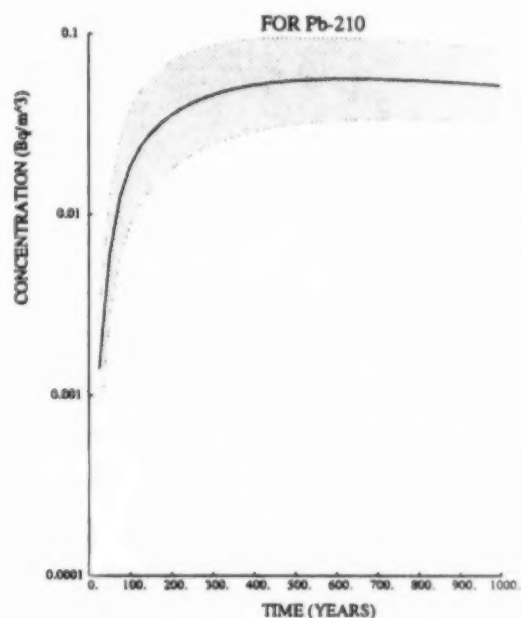
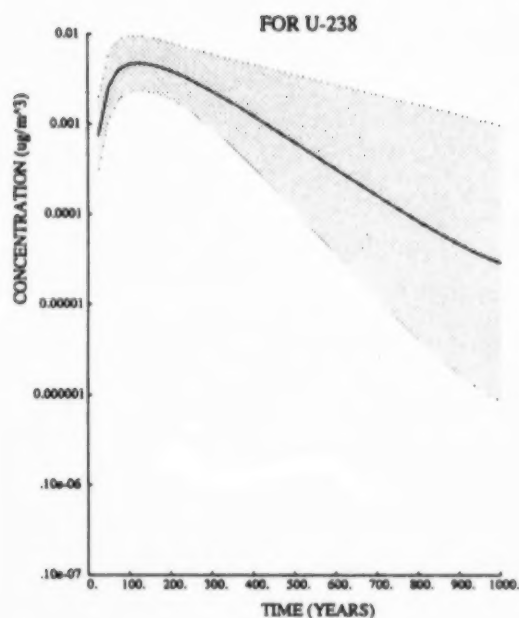


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 2 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

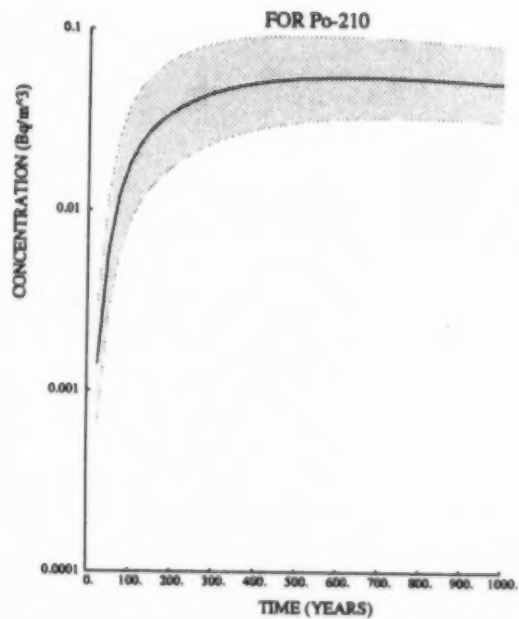


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 3 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

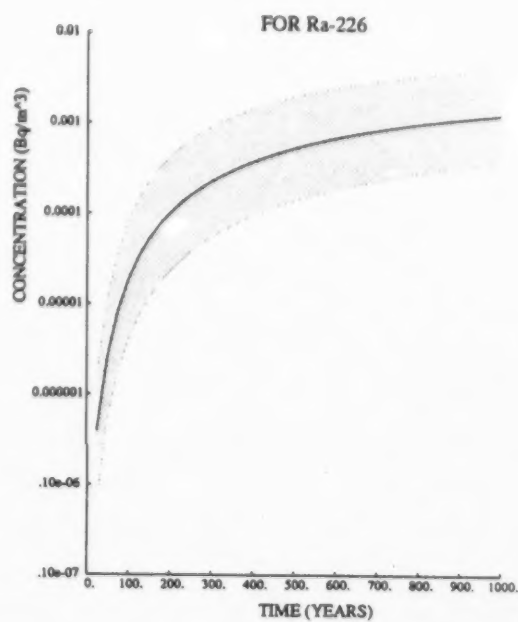
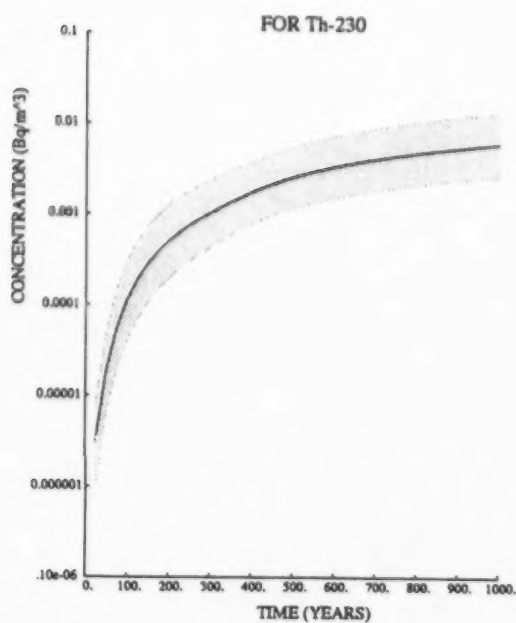
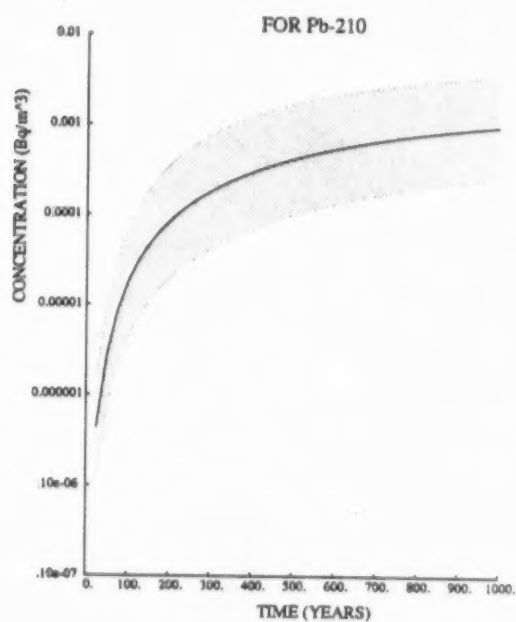
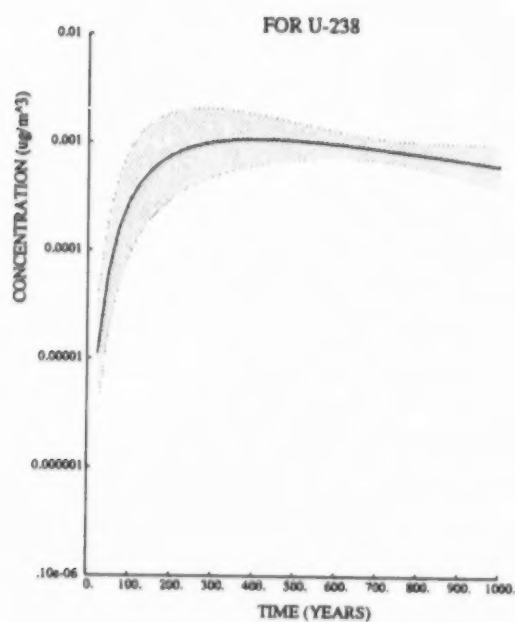


FIGURE E.2.19 SOIL CONCENTRATION vs. TIME
IN LAYER 3 AT WOLLASTON LAKE RECEPTOR
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

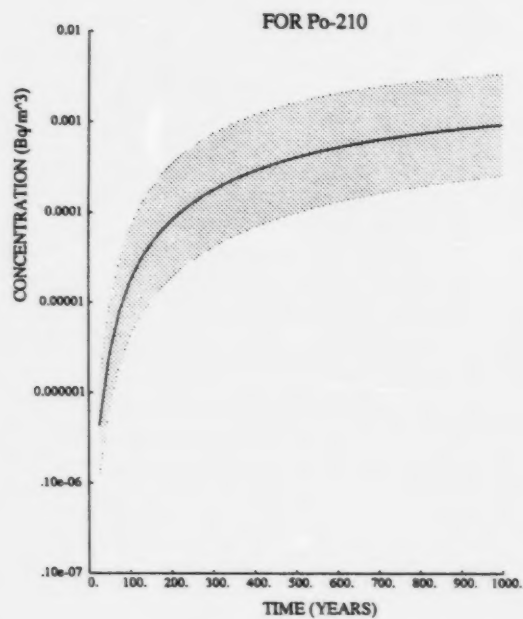
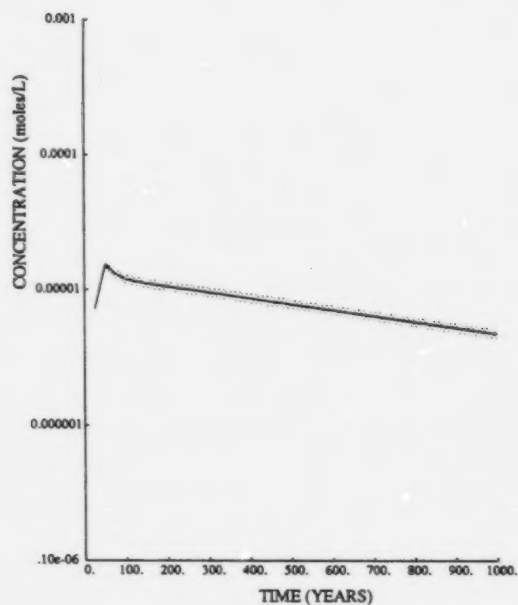
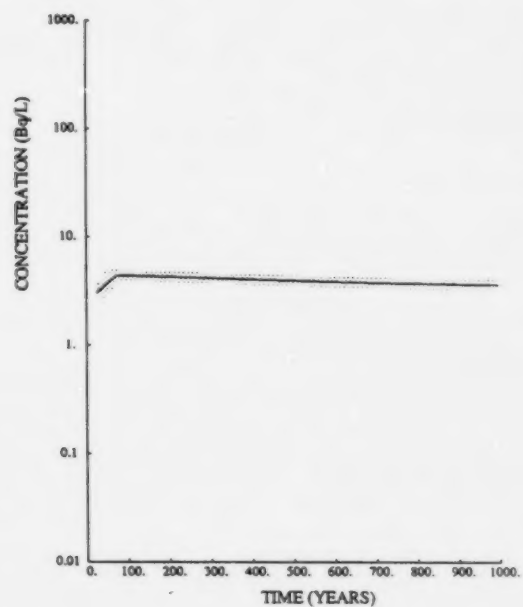


FIGURE E.3.1 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

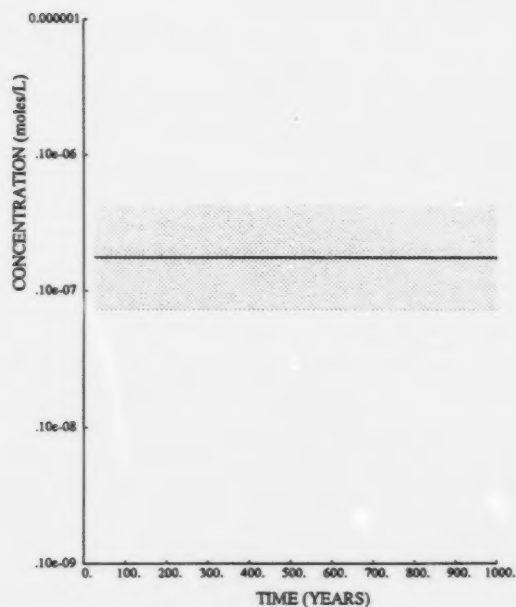
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

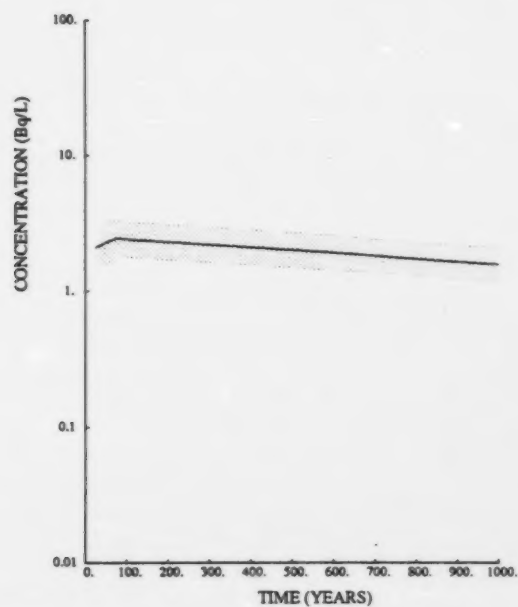
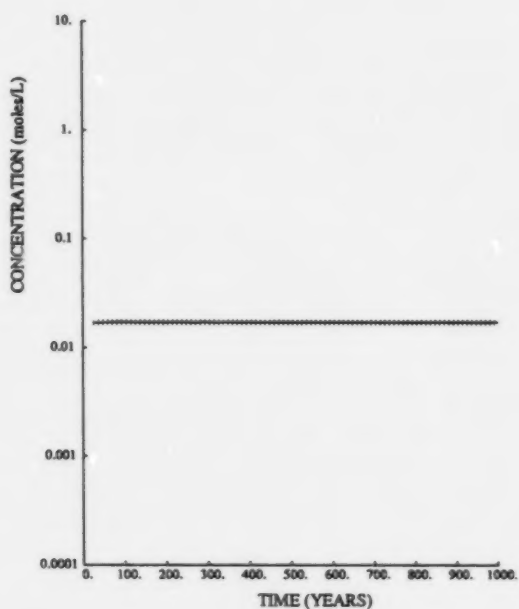
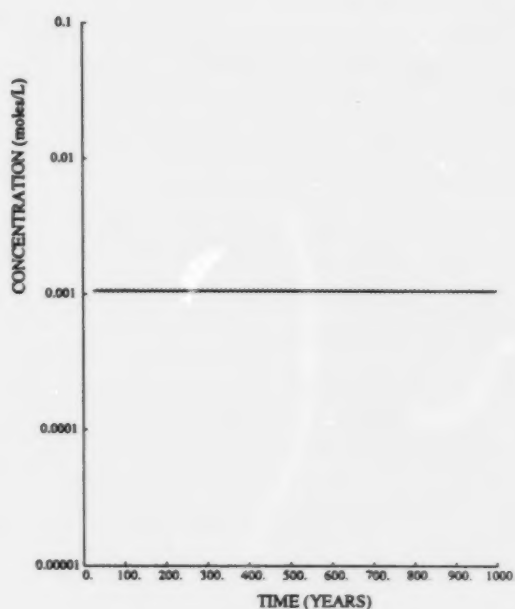


FIGURE E.3.1 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

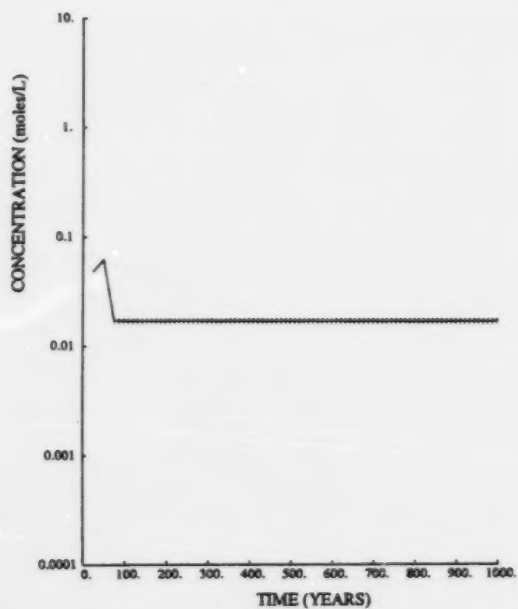
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

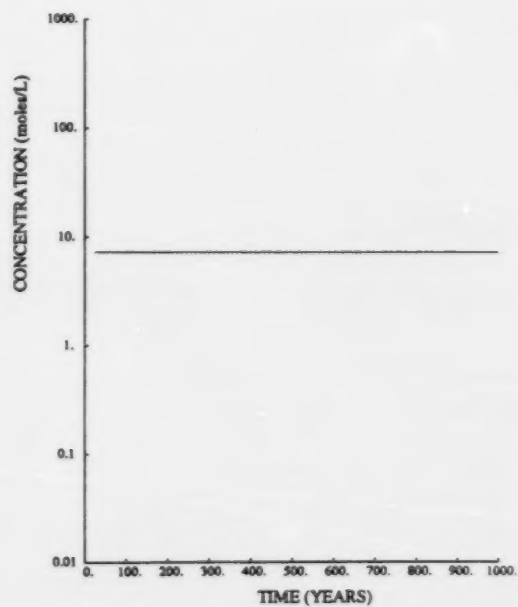
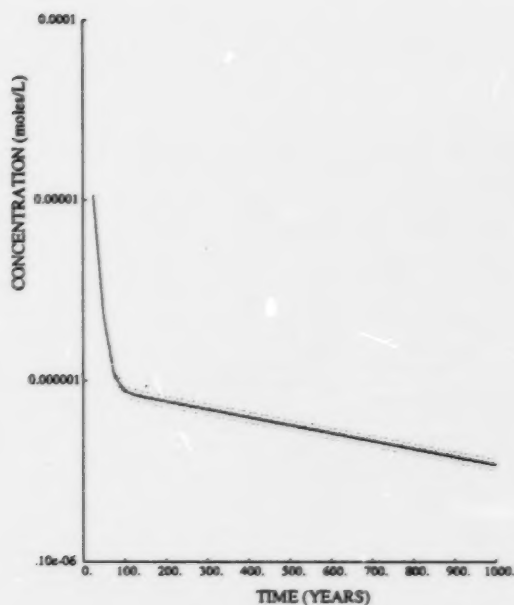
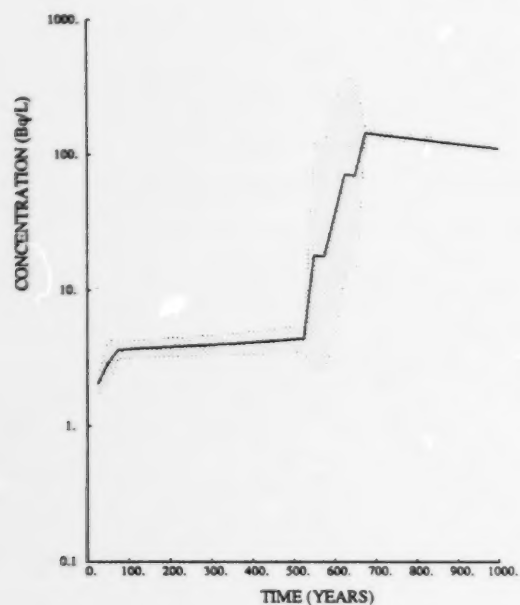


FIGURE E.3.2 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

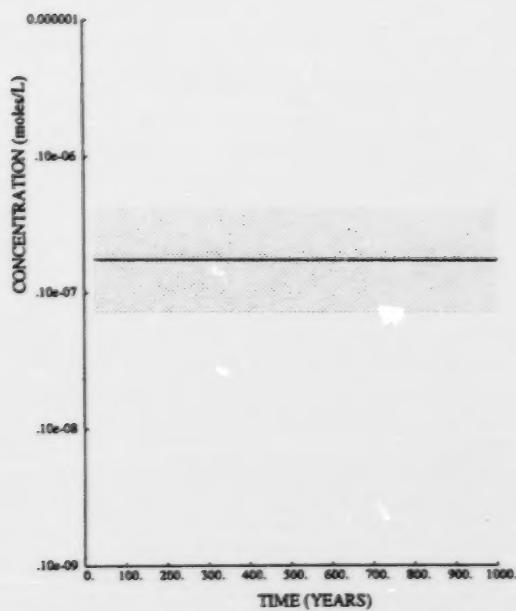
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

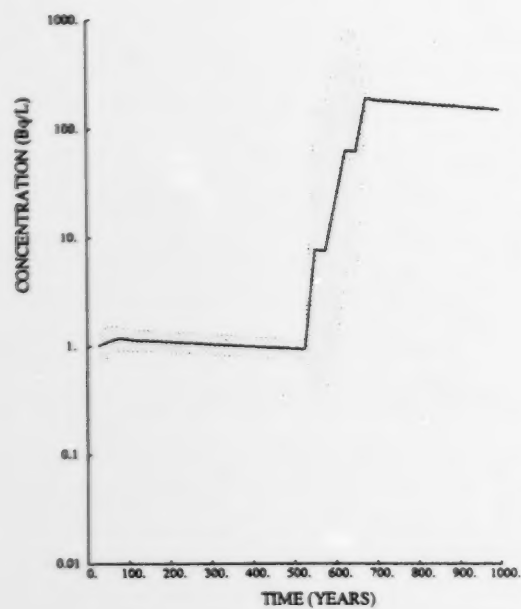
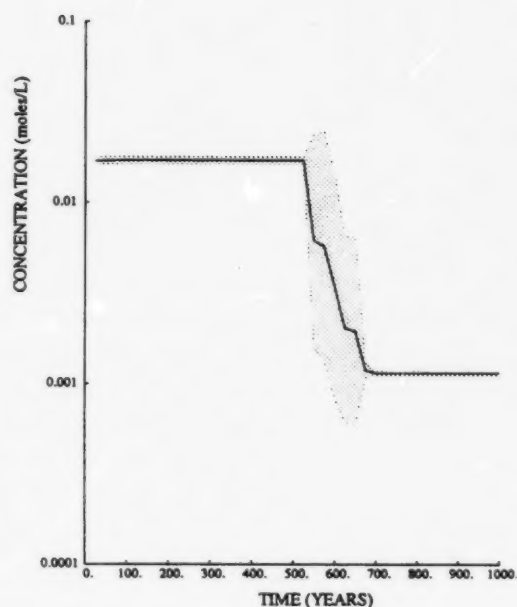


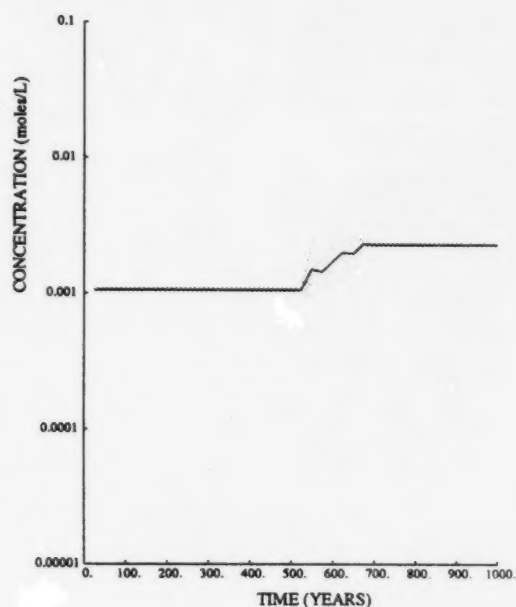
FIGURE E.3.2

CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

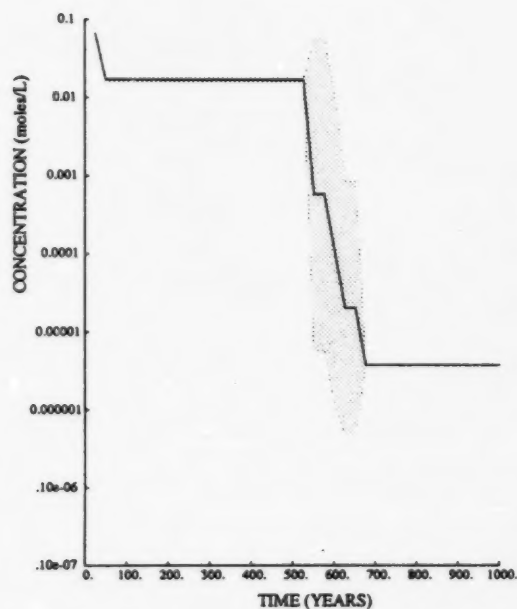
FOR CALCIUM



FOR CARBONATE



FOR SULPATE



FOR pH

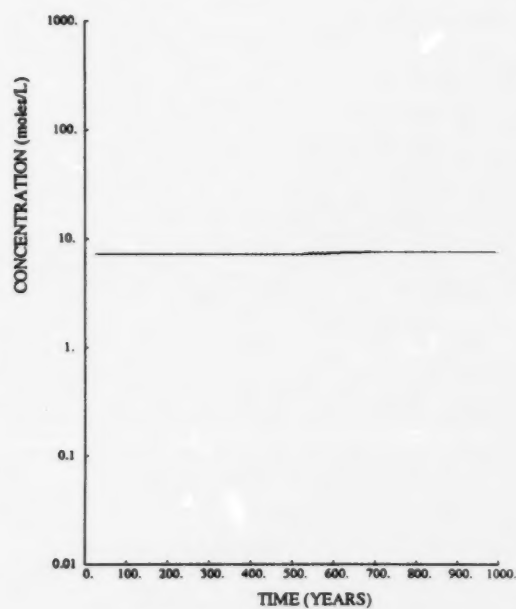


FIGURE E.3.3 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

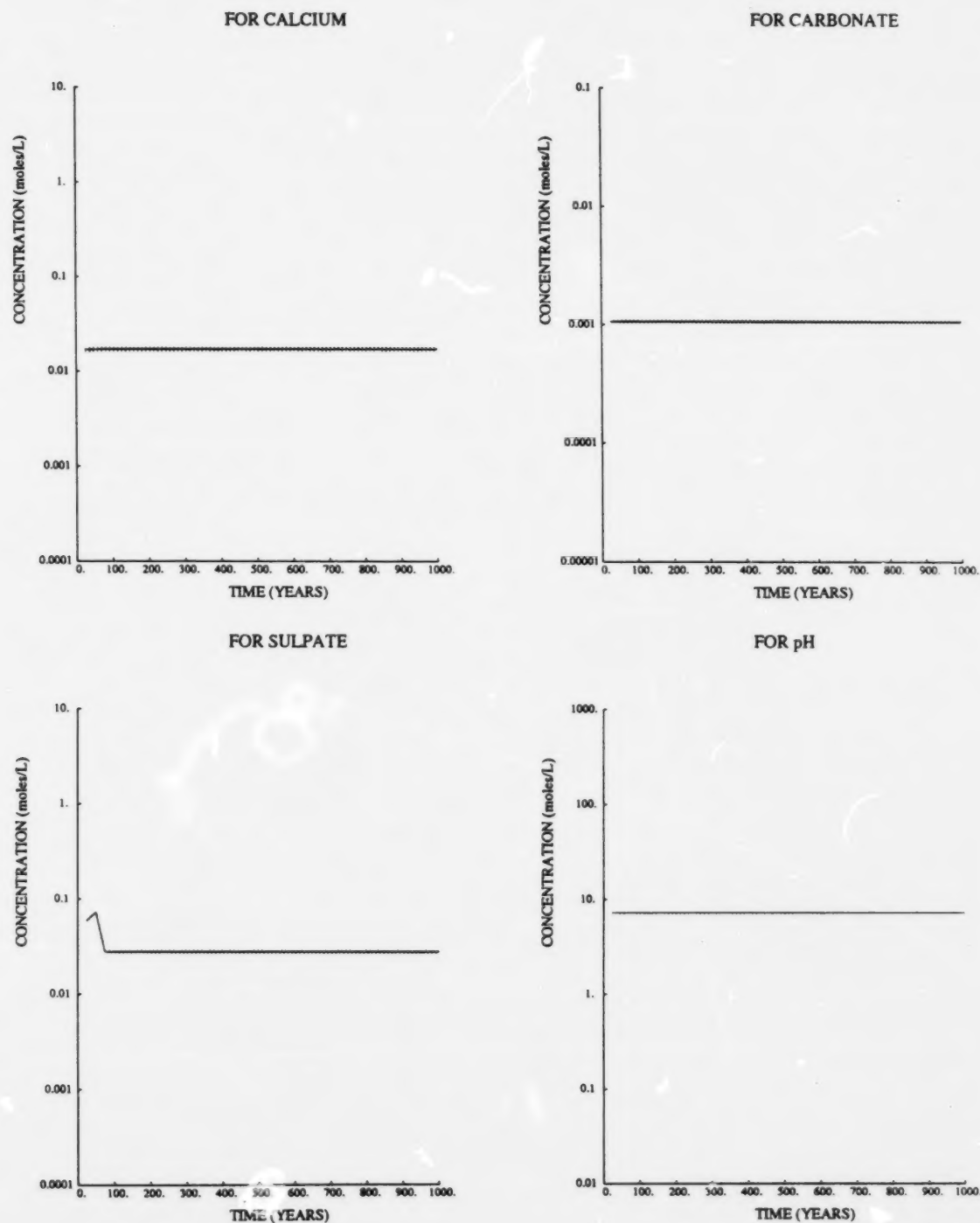
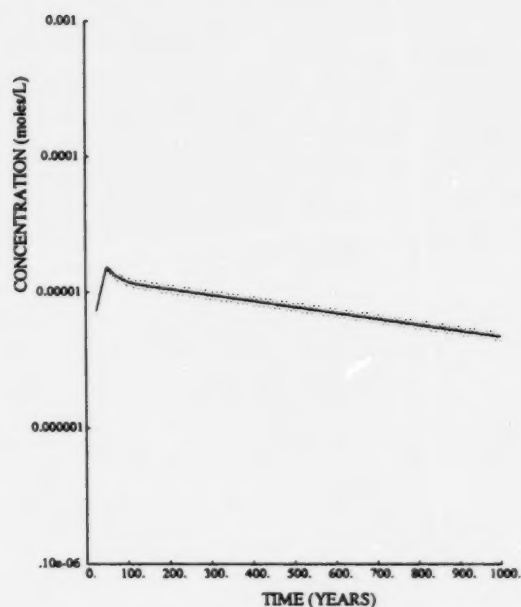
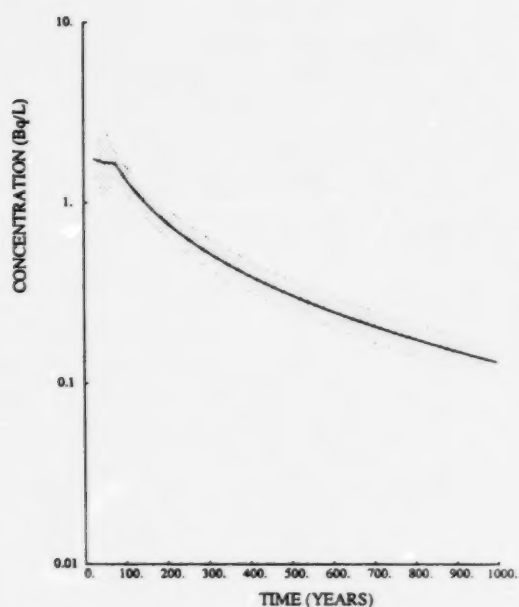


FIGURE E.3.3 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 3
GEOMETRIC MEAN OF 5 TRIALS

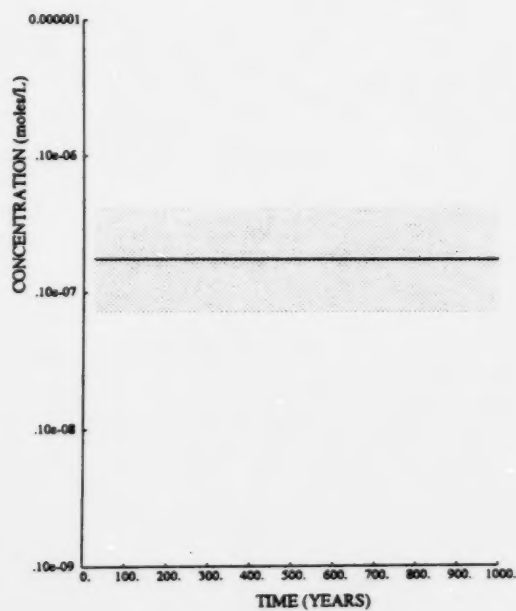
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

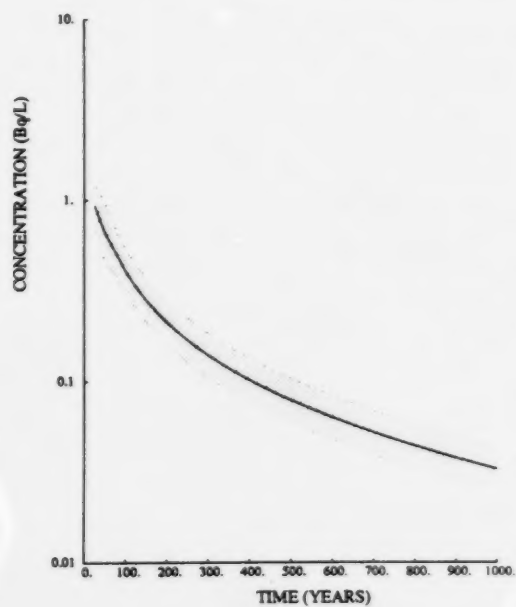


FIGURE E.3.4 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

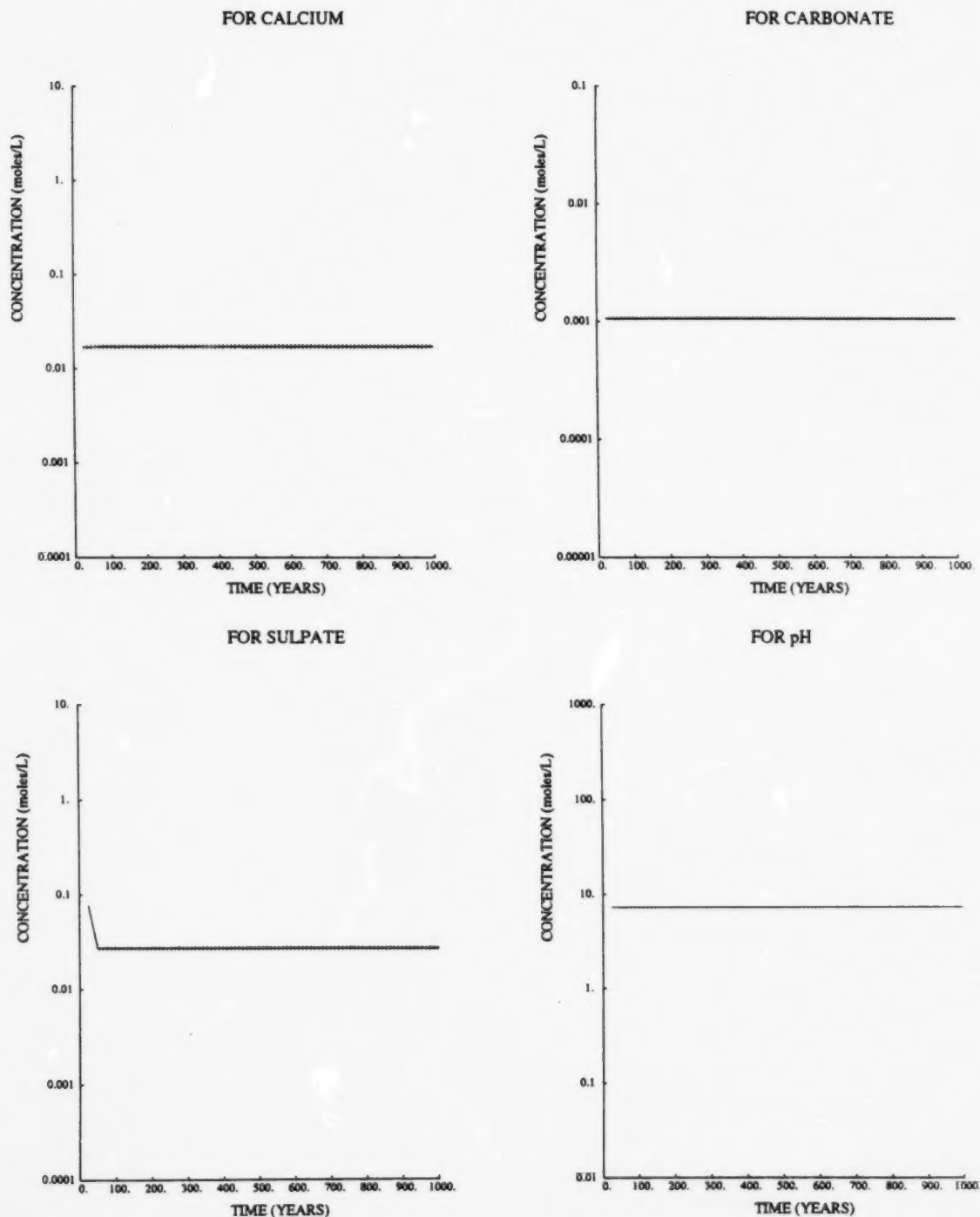
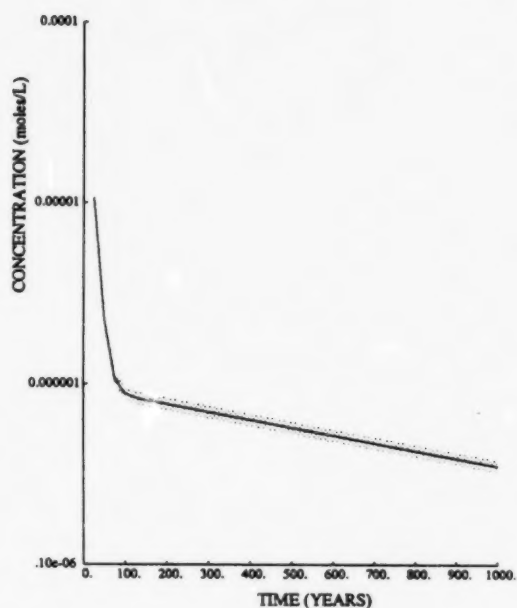
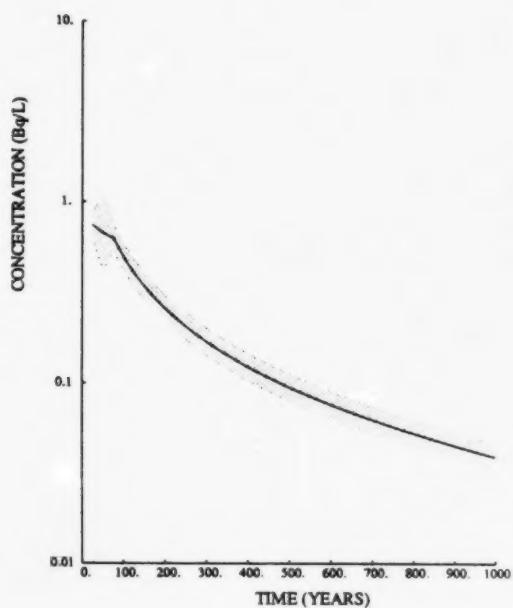


FIGURE E.3.4 CONCENTRATION vs. TIME
FOR SCENARIO 1, IN BOX 7
GEOMETRIC MEAN OF 5 TRIALS

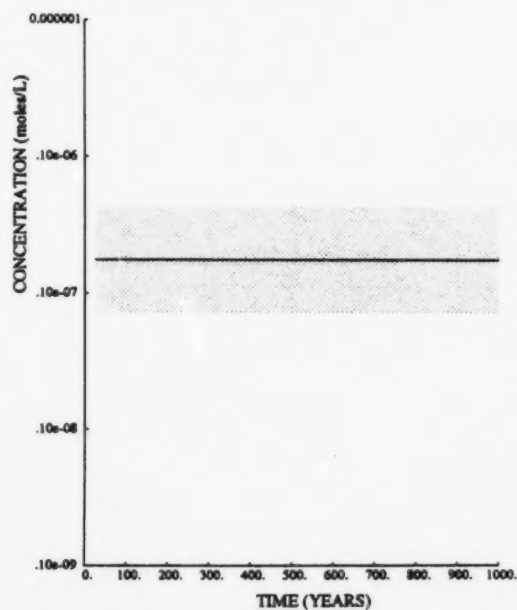
FOR U-238



FOR Ra-226



FOR Th-232



FOR Pb-210

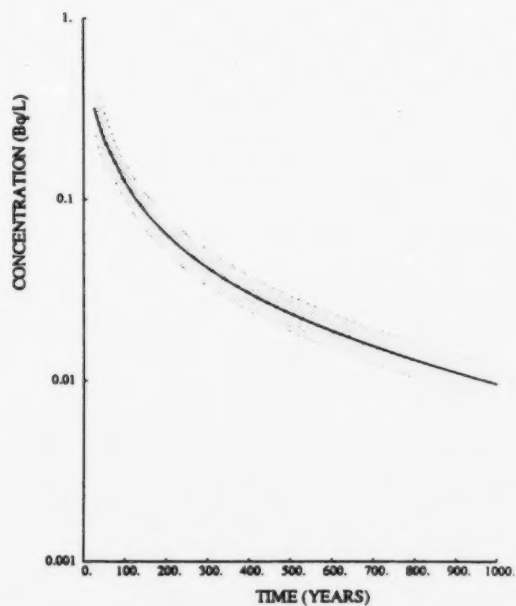


FIGURE E.3.5 CONCENTRATION vs. TIME
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS

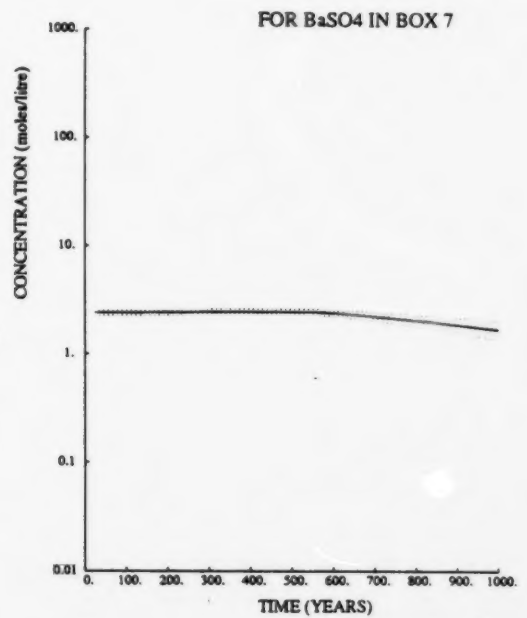
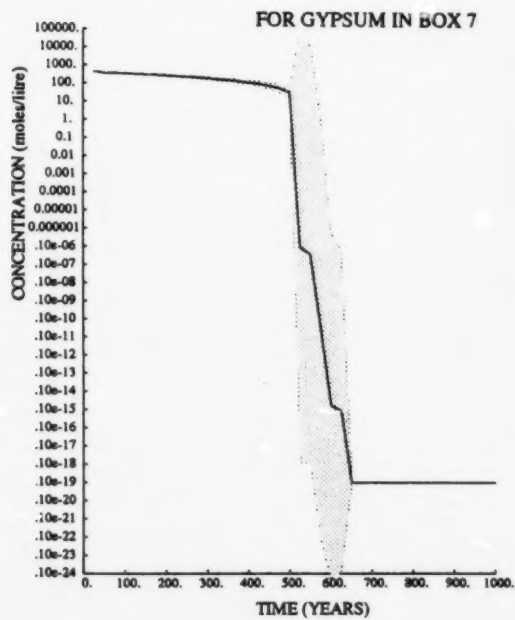
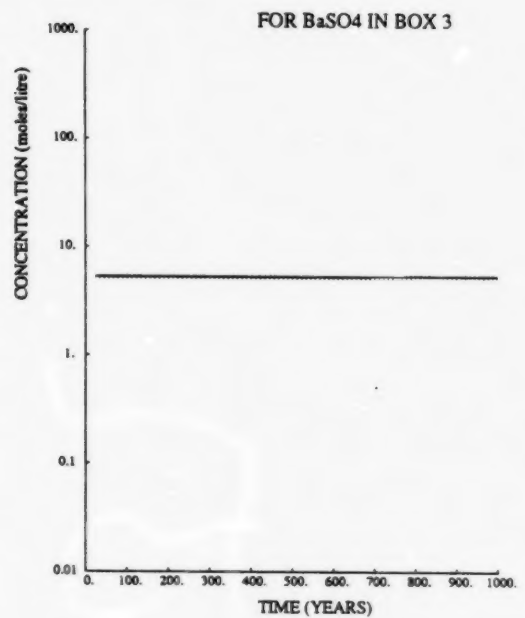
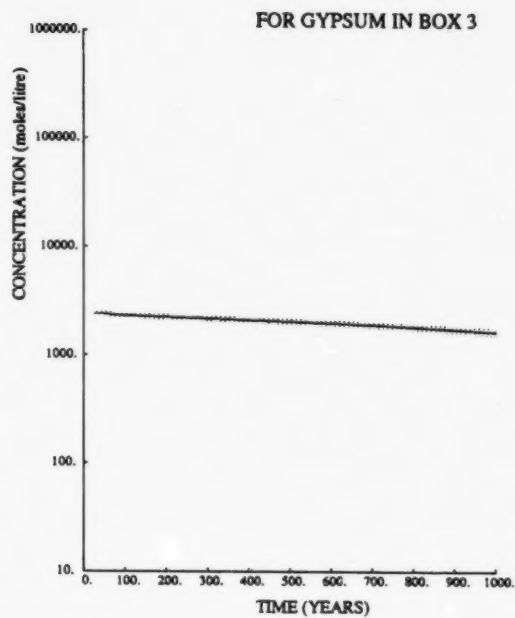
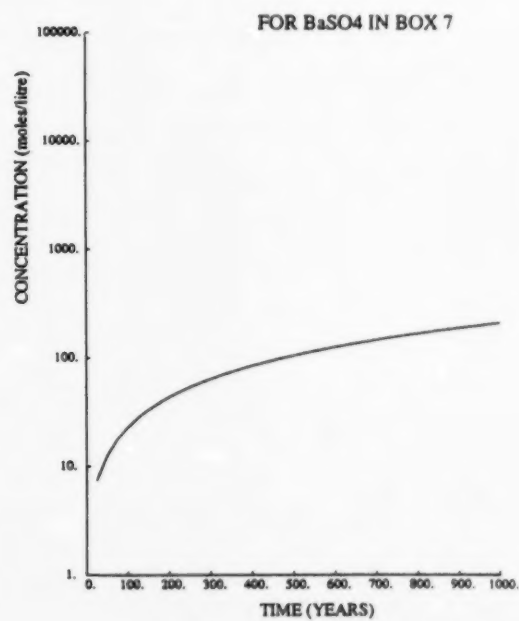
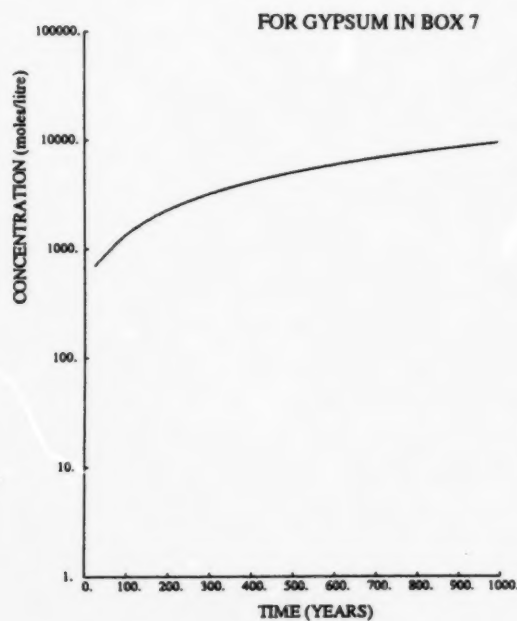
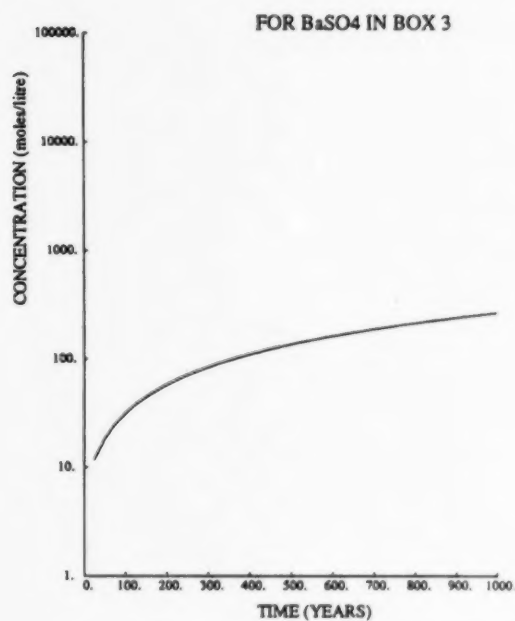
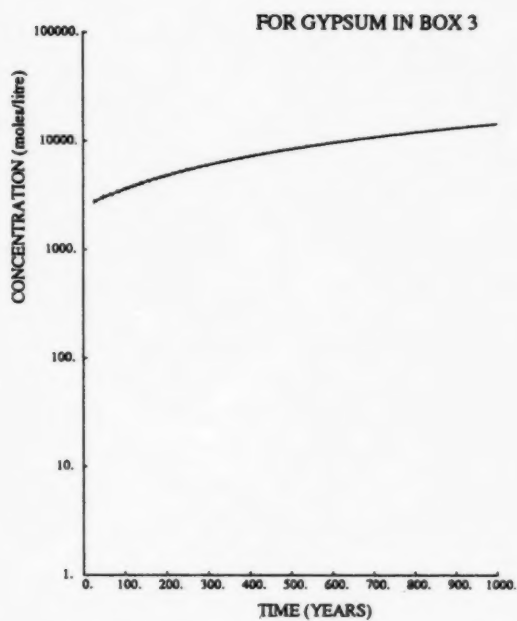


FIGURE E.3.6 CONCENTRATION vs. TIME
FOR SCENARIO 1
GEOMETRIC MEAN OF 5 TRIALS



solid phase concentrations (Figure E3.6) for gypsum and barium sulphate increase over time when the Parks Lake concentrations are used as estimates of the groundwater concentration. This results from the fact that the water entering the tailings is supersaturated with respect to gypsum and barite. Accordingly, upon contact with the tailings, the model calculates these constituents precipitate to maintain chemical equilibrium in the porewater. This causes the solid phase concentration to increase over time.

An increase in solid phase concentration provides a larger mass of solid with which to coprecipitate Ra-226. In other words, this system has a larger capacity for "sorbing" Ra-226 on the solid phase over time. This results in the porewater concentration of Ra-226 and Pb-210 decreasing over time, as shown in Figures E3.3 and E3.4.

E.4 Software Quality Assurance

Software quality assurance attempts to verify that a computer code does what it was designed to do. It involves definition of software objectives, a software development process, application of software standards, verification and testing among other elements. The overall approach and the specific techniques used by SENES (1984, 1985, 1986) were generally adopted. Additional code tests designed by BEAK were also developed. In this section, the general approach is highlighted. Then specific attributes of the QA procedure are summarized.

The quality assurance program of this project was a particular challenge because of the need to modify the existing data management structure, to modify some existing subroutines and to retain many in their intact state, and to modify the source model term. Its implementation was facilitated by use of a program developed previously and knowledge of the code. Software development, involved in this undertaking, has two levels of difficulty. The first and easier level comprised development of modules which the existing software and its documentation provided for explicitly. The second level and greater challenge involved modifying the existing subroutines to provide for new computational objectives. These modifications required some resourcefulness in software engineering because, in contrast to the other work, they involved knowledge of interfaces and areas of software interaction points, which were not originally designed to be extended.

E.4.1 Software Development Process and Standards

Computer software embodies an algorithm in a structure. The numerical accuracy that the software can achieve depends, in part, on the algorithm used. Accuracy and most other aspects of quality depend even more strongly on the structure of the software.

The software team's first task was to examine the available documentation for the existing system and to determine where alterations in the algorithms impacted software structure. In particular, opportunities to exploit any software "hooks" that may have been built into the program by its developers were sought. Then any additional information needed was defined and gathered either by reviewing the program codes themselves, and/or through communication with the SENES personnel.

At this point in the process of software development, alternatives with respect to design modifications were defined. The major alternative for data management was summarized above. On the basis of this outline, decisions on preferred alternatives were made by trading off various advantages and disadvantages with respect to hardware and software capabilities. To specialists in the field of computer science, the range of options for the software team were relatively limited: choices of hardware and software, including programming language and operating system, were already made; and software capabilities were defined by the scientific team. To obtain the greatest overall software quality, the selection process used was in line with Boehm's 1978 "software quality characteristics tree". A preferred alternative was selected and a detailed design was generated. This resulted in descriptions of changes to algorithms that are used to represent models in the existing software, and descriptions of new algorithms. These details were reviewed with the appropriate SENES team members, and others and then implemented.

The modified sections of code and new code were written stubbing new low-level modules for subsequent completion. Writing of code proceeded on two parallel paths. Coding for pathways proceeded in parallel but independent of coding for the source term. Walk-throughs, involving the scientific team, and the software development team, were conducted to expose any inconsistencies with existing codes, linkage problems or remaining misunderstandings about algorithms. Any that were found, were corrected.

Stubbed modules and other components were completed at this stage. Final code walkthroughs were organized and corrections made thus terminating code development. Hooks in the code were provided to handle additional concepts and equations when time in this project did not permit final development of code, its implementation, and quality assurance checks.

Coding was organized along the lines of a Chief Programmer Team. Overall development responsibilities, including design, were in the hands of the Chief Programmer. The actual design of the data structure was determined and developed by the Chief Designer, Designer Consultant who have backgrounds in computer science. Applications programmers with backgrounds in computer science, geology, and chemical engineering were responsible for developing new code or modifying existing code to achieve the requirements of the source term, pathways equations and of the code design. Applications programmers were also responsible for stubbing appropriate modules and conducting walkthroughs of component modules in consultation with personnel knowledgeable about the science behind the equations. The function of Program Librarian/Secretary was carried out by an applications programmer who was also a member of the scientific team. This structure ensured the availability of a "critical mass" of sound software shells but also kept the project at a manageable size.

Software Standards involve software design, management of code development, and code documentation. Top-down Design, which employs methods and symbolisms similar to those of Yourdon and Constantine (1978) in designing and expressing software structure was used. This is one member of a class of similar methodologies in use by most successful software development organizations. Various techniques were used in code management to ensure the integrity of its software products. This was particularly important, owing to the heavy use of COMMON blocks in the existing codes (Wulf and Shaw, 1973).

Provisions in the existing code to display information about the contents of storage and program states, were extended in the new and/or modified code.

Full use was made of the (albeit) limited possibilities for writing structured code in FORTRAN. The code is portable and readily adaptable to other systems.

The standard for documentation developed by SENES for the existing software was maintained or modified as follows. The procedure for tabularizing variables, etc. was retained and summarized in this report. Full documentation, however, was not made in this report because the objective of this project was not to produce a user's manual.

E.4.2 Verification and Testing

The objective of this phase was to verify the detailed behaviour and correctness of the modified software.

With respect to quality assurance nomenclature, two terms can be defined: model verification and model validation. Model verification is defined here as "code verification" - the checking of the computer code to ensure that it performs as specified. "Model validation" is defined here as a comparison of the quantitative calculation by the computer code with field and laboratory data. The quantitative calculations result from the conceptual model and the process of developing its algorithm and computer code. Definitions of the terminology: model construction, model calibration, model validation and model simulation, and model validation tests are given elsewhere (e.g., Thomann, 1983).

Two types of code verification tests were developed. First, "black box" tests were developed on the basis of what the code is supposed to do, without knowledge of how the code works. For example, an external analytical solution was available as a restricted test case. The code results were then compared to the analytical solution results. These were used for the source term subroutines, the river/lake water, the groundwater and air pathways, the food-web and dose-contaminant aspects of the code.

Secondly, "white box" tests were utilized which are dependent on a knowledge of the code itself. In such tests, cases were developed to ensure that all parts of the code are exercised. For example, transfers of control were tested wherever possible. In addition, for all major subroutines, one technical person not directly involved in flowcharting and coding the subroutines, inspected the equations and the coding and transfer of control statements to ensure that the coding was consistent with objectives of the calculations.

All subroutines were broken down into component parts and the white box tests conducted in conjunction with black box tests. For example, for calculation of source term pH, hand calculations were prepared for all major cases involving solids present and not present (gypsum and calcite present, gypsum only present, calcite only present, neither solid present) and code calculations compared with the hand calculations and to test the transfer of control. Similar tests were carried out for new subroutines using nominal input values, and the code calculations were checked by hand. The most frequent error encountered related to the order of magnitude for output values on initial trials. Whenever errors were encountered, the code was inspected and revised, and the white box test repeated until valid output was obtained.

The different components were linked and the calculated values at different points along the pathway were inspected. For example, predicted radionuclide concentrations in the tailings pore water, receiving water and atmosphere were inspected to assure that they were within the range of typically measured background values. Unreasonably high values were found to be indicators of erroneous conversions of concentration units or of problems in the source term components.

Then similar to SENES (1986), deterministic runs involving nominal values and extreme values and probabilistic runs were made after the logic of the order of all statements was examined via a walkthrough. In these walk-throughs, the input and output generated by the code was carefully examined and checked for numerical accuracy by the modelling scientists and the programming team. Code calculations were hand-checked to ensure that input and output were passed correctly among the various subroutines.

A limited set of probabilistic runs was then carried out using large time steps and a limited number of runs. These runs were carried out to check that the evolution of the source term over time proceeded as intended, and that the system model functioned properly in general. In these tests, some output variables were initially found to "blow up" (approach extremely high or low values). For cases where the equations allow negative values but where physical reality sets a minimum value (e.g., greater than zero), the values are appropriately constrained.

Code limitations occur, resulting from model assumptions and code design. For example, more substances can be considered but code alterations are required to handle the

additional elements and chemical behaviour involved. The desire to handle additional substances was one of the original specifications of the generic data management structure, but was discarded to allow for ease of following code structure and error "debugging". The limitations are documented in this report, particularly by stating assumptions upon which the equations are based. These limitations are described throughout the main body.

E.4.3 White and Black Box Tests

The following tests were made:

- o flows were checked to ensure:
 1. total into tailings = total out of tailings,
 2. flow rate in = flow out of each box,
 3. flow in any direction (North Dam, South Dam, Parks Lake) added up to the total flow for that direction,
 4. all flow out of groundwater pathways equalled that amount entering the tailings;
- o in groundwater subroutine, air subroutine, lake subroutine and food chain model, hand calculations and printing of input to verify concentrations out;
- o hand calculations for units compatibility;
- o box diagrams, four different times, to assure that flows between tailings boxes were assigned correctly;
- o ingrowth of radionuclides in source, groundwater, lake and soil; Pb-210 ingrowth was not included on UTAP3 for soil and was coded in; and
- o equilibrium calculations by hand for source term for gypsum, radium-226, Th-230 and Pb-210 to assure that calculated concentrations were correct.

E.4.4 Quality Assurance Summary

As in the development stages of the systems model, the QA strategy included many activities and was integrated into all phases of software development. Formal and informal reviews were used during the early stages of software development to reach a consensus on component model approach and structure, and to test the functioning of the various modelling components.

The data management, random number components and associated data assignment component were carefully tested during previous studies. Additional testing was carried out to the components added by BEAK for this demonstration (e.g., new input data, new 'subroutine cell' component).

The component models of the system were subjected to a rigorous QA program. Initially, the modelling specifications, conceptual design and mathematical formulations were subjected to walk-throughs and peer review. Problems in adapting the existing component models and developing new component models were identified and rectified before computer coding or modifications to existing codes were carried out.

After new coding was complete, the new component subroutines were tested individually and in small groups. Initially, models were tested deterministically, using nominal values for input parameters. All substructures were hand-checked to verify computational correctness. As in the SENES Phase III assessment (1986), individual component models were then evaluated probabilistically. The source term components were tested most rigorously, since they are the most complex, and are substantially altered to this version of the systems model.